AFIT/GSM/LSY/92S-2

A METHODOLOGY FOR PROJECT SELECTION
USING ECONOMIC ANALYSIS AND
THE ANALYTIC HIERARCHY PROCESS

THESIS

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THESIS

Presented to the Faculty of the School of Systems and Logistics
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Master of Science in Systems Management

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Preface

The intent of this research was to explore an alternative method of conducting an Air Force economic analysis involving qualitative factors. Our examination of the present system of accounting for qualitative influences in an economic analysis suggested that a more scientific approach was needed.

Our study demonstrated the application of a multiple criterion decision making aid to an Air Force economic analysis that was previously performed using traditional techniques. The results of our research indicated the practicality and usefulness of computer-based decision making tools like the one in this study.

We wish to thank a number of people who provided us with an extensive amount of advice and support in writing this thesis. We are genuinely grateful to our advisors, Major David Christensen and Major Wendell Simpson, for the wise counsel that they provided. We are also thankful to Mr. Randy Bradley for providing us with the Air Force data that was used in this study. We would like to mention Dr. Roland Kankey, Ellen Mauritz, Steve Connair, David Graham, and Janet Gaston for their contributions. Finally, this thesis would not have been possible without the support of our wives, Donna and Tish. Their patience and understanding were vital to the success of this project.

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Abstract

This study examined the applicability of a multiple criterion decision making (MCDM) method, known as the Analytic Hierarchy Process (AHP), to economic analysis decisions involving project selection. A survey of the literature and current practices revealed that qualitative criteria were not adequately represented in a typical economic analysis of projects. Several MCDM methods were examined and the AHP was found to be the most promising technique to rate projects on a ratio scale. Two types of project selection problems, those involving non-mutually exclusive alternatives and those involving mutually exclusive alternatives, were studied. It was determined that the AHP was applicable to both types of problems.

An investigation of the literature regarding non-mutually exclusive problems revealed that zero-one programming could be used to select a subset of the alternatives with the largest total AHP rating.

With the help of a software package called Expert Choice, the AHP was then applied to a previously completed Air Force economic analysis (with mutually exclusive alternatives) and the results were evaluated. This study concluded with the recommendation that the Air Force formally adopt the AHP into its economic analysis procedures.

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I. Introduction

Capital Budgeting and the Analytic Hierarchy Process

This study examined the capital budgeting process. Capital budgeting is the making of long-term investment decisions (21:673). It is a four-step process consisting of the following: 1) identifying possible projects based on opportunities and/or needs, 2) collecting detailed information about each project, 3) choosing (and implementing) one or more of the projects based on their relative merits, and 4) evaluating the performance of the implemented project(s) (27:9). This study was limited to steps one through three. Air Force Regulation (AFR) 173-15 and Department of Defense (DOD) Instruction 7041.3, both entitled *Economic Analysis and Program Evaluation for Resource Management*, address the topic of capital budgeting (13; 14). They refer to capital budgeting as "Economic Analysis," or "Cost-Benefit Analysis" (13:6; 14:2). The terms "capital budgeting" and "economic analysis" are used interchangeably in this study.

When the set of projects under consideration are mutually exclusive in the sense that each is an alternative way to satisfy the same opportunity or need, step three of the capital budgeting process consists of choosing only the one "best" project. If the budget is limited, any alternative that exceeds the budget can be eliminated at the outset of the selection process. If none of the projects are mutually exclusive, they are ranked in order of decreasing desirability, and the best "x" projects are selected, or all of the projects that meet some minimum standard of acceptability are selected, or projects are selected until all of the available funding is exhausted. Of course, it is possible to have a collection of projects where some are mutually exclusive and some are not. In this case, the process for mutually exclusive projects could be conducted first, followed by the process for the remaining purely non-mutually exclusive projects, if necessary.

The criteria for choosing among the projects can be grouped into the following three categories: 1) financial quantitative, 2) non-financial quantitative, and 3) qualitative (26:59). Numerous techniques and suggestions for analyzing the financial category are available (21:673,674; 14:9-17; 4). The technique preferred most by theorists and practitioners alike is net present value (21:674,677-679,723; 14:12; 4:v). The net present value of a project is the sum of all of the expected cash inflows minus the sum of all of the expected cash outflows over the life of the project, taking into account the time value of money (the fact that a dollar today is not worth the same as a dollar five years from today). Net present values of the various projects can be compared directly (21:675). Any given non-financial quantitative criterion can also be compared directly among projects (13:9). When alternatives have unequal economic lives, the uniform annual cost technique may be used (14:14). This technique, however, is only valid when alternatives have the same annual qualitative output (14:19). No obvious technique exists for dealing with unequal qualitative criteria (13:9; 22).

> Characteristics such as . . . miles/hour . . . can sometimes be quantified in nonmonetary terms. In such cases, direct comparisons among these measures should be undertaken. In others, narrative description of the characteristics as a cost or a benefit may be the most that can be done. (13:9)

Another problem involves comparing criteria with each other. A cost analyst at Headquarters Air Force Systems Command said that a simple weighted factors approach is often employed (after somehow "quantifying" the qualitative factors). Another alternative is to draw up tables listing the characteristics of the different alternatives, which are then compared side by side (25).

The Analytic Hierarchy Process (AHP) is a systematic four-step process for solving multiple-criterion problems (39:96). It is a technique that allows the decision maker to incorporate the qualitative criteria into the selection process (29). In addition, the AHP accommodates the relative importance of the various criteria (39:96). A complete description of the AHP is given in Chapter II.

Problem Statement and Investigative Questions

The problem addressed by this study is the lack of any definitive directions within the Air Force for conducting a thorough and systematic economic analysis. AFR 173-15 and DOD Instruction 7041.3 give little useful guidance on how to deal with qualitative criteria, or on how to incorporate the relative importance of the various criteria in a systematic fashion.

Several manuals have been developed to try to fill this void. An Air Force Systems Command manual offers an easy to read step-by-step set of instructions for conducting an economic analysis (23). It includes suggestions on how to deal with qualitative criteria (23:18-20). It also gives an example of an economic analysis where qualitative criteria are used. This manual, however, only mentions the need to assign weights to the criteria (23:18). No example of this is given. A manual prepared by the URS corporation and the Oak Ridge National Laboratory serves as another comprehensive source of instructions to anyone wanting to conduct an economic analysis (35). This manual includes three sample economic analyses that contain weighted qualitative criteria. In none of the examples, however, is any attempt made to indicate the importance of the qualitative criteria relative to the quantitative criteria, other than to say that qualitative criteria should be used sometimes and ignored other times (35:52).

The investigative questions for this research paper are

1. How does the business community in general, and the Air Force specifically, make capital budgeting decisions/conduct economic analyses?
2. What is the AHP? Can it be applied to capital budgeting/economic analysis problems? And can a standardized comprehensive economic analysis procedure, which includes the AHP, be set forth?

The first question was answered through a review of the pertinent literature, and through interviews with selected Air Force personnel. The second question was answered by a review of the applicable literature, and by a trial of the AHP on an actual Air Force economic analysis. One additional intended benefit of this thesis was to demonstrate an objective and systematic method for including qualitative criteria and for assigning relative weights to all of the criteria in an economic analysis.

Overview of Chapters II through V

Chapter II consists of the review of the capital budgeting/economic analysis literature, the review of the multiple criterion decision making literature, including the AHP, and the results of the interviews with selected Air Force personnel. Chapter III is a description of the method that was used to accomplish a trial economic analysis on a set of Air Force data. Chapter IV gives the results, along with an analysis of the process used to obtain those results. Chapter V presents some conclusions and recommendations.

II. Literature Review

The topics covered in this chapter include capital budgeting/economic analysis, multiple criterion decision making (MCDM) in general, and the Analytic Hierarchy Process (AHP) specifically. In all, eight MCDM methods are examined. Following a detailed treatment of the AHP as a method for selecting a single "best" alternative solution to a MCDM problem, the topic of zero-one integer linear programming is discussed. It is shown that zero-one integer linear programming may be applied to the output of the AHP to select multiple alternatives in a MCDM problem.

Capital Budgeting/Economic Analysis

Capital budgeting, or economic analysis, as it is referred to in the Air Force, is a four-step process. The first step, identification of possible projects, should be done with an organization's strategic objectives in mind. Step two, data collection, is thought to be the most difficult step. This is due to the frequent unavailability of accurate, timely, or pertinent data. The third step involves deciding what to invest in and determining the best methods for financing projects. The final step (not addressed in this study) involves evaluation of implemented projects during and after their period of implementation (27:10-14).

<u>Economic Analysis According to AFR 173-15 and DOD Instruction 7041.3</u>. Air Force Regulation 173-15 is the governing regulation for conducting economic analyses in the Air Force (13). It is the Air Force's implementation of DOD Instruction 7041.3 (13; 14). These two documents should be used in tandem. The DOD Instruction contains a much more thorough treatment of the topic of economic analysis, but AFR 173-15 is more up-to-date and it contains specific information pertinent to the Air Force.

The general philosophy behind the Air Force economic analysis process can be acquired by reading the early sections of both documents. Economic analysis is an integral part of the DOD Planning Programming and Budgeting System (14:3). An economic analysis should be prepared if the total investment is expected to exceed one million dollars (two million dollars for military construction or military family housing projects) (13:3,13). Once it is determined that an economic analysis is necessary, it should be initiated as early in the acquisition process as possible (14:4). "A good economic analysis *systematically* examines and relates costs, benefits, and risks of various alternatives" (13:3). "A complete (EA) covers both the monetary and the nonmonetary consequences of each alternative" (13:3). It is important to note that the economic analysis serves only as one tool for making the project selection decision.

> A complete economic analysis . . . should be considered as one of the inputs required to make a proper decision concerning the use of resources, and not the decision making process itself. (14:8)

The two documents include detailed discussions on what is required in an economic analysis. A completed economic analysis must include the following: 1) an executive summary, 2) a clear statement of the problem, 3) relevant assumptions, criteria, and variables, 4) a complete list of alternatives, 5) a thorough description of each feasible alternative, 6) estimated costs and benefits of each alternative, and 7) a comparison showing the relative strengths and weaknesses of each alternative and identifying the most effective alternative (13:6). Various other requirements, some of which are mentioned here, are contained in AFR 173-15.

> All economic analyses and program evaluations must show the source (including the date) of data used. Analyses in which the outcome may depend on time sensitive data (e.g., the influence of foreign exchange rates on overseas military construction projects) should provide for simple insertion of new data. (13:11)

A sensitivity analysis should be performed on all key variables and assumptions whose values are uncertain. Alternative methods of financing, such as buy, lease, third-party financing, and time payment should be evaluated (13:3). The regulation addresses alternative methods of analysis in the following statement.

> When unusual methods are used, an explanation of those methods as well as the rationale for their use are mandatory. This is not intended to discourage alternative approaches, but rather to ensure that innovative techniques can be fairly evaluated. (13:11)

It is a mandatory requirement to use present value techniques in the financial portion of an Air Force economic analysis. Both AFR 173-15 and DOD Instruction 7041.3 have sections that describe in detail the concepts of present value and discounting (accounting for time differences) (13:9; 14:12-17). Two types of discount rates, "real" and "nominal", are used in the discounting of cash flows. Inflation is what differentiates real from nominal discount rates. Real and nominal discount rates are related by the following formula:

$$R = [(1 + N)/(1 + I)] - 1 \qquad (1)$$

where R is the real discount rate, N is the nominal discount rate, and I is inflation (21:715,716). Dollars that include inflation are called "then-year" or "nominal" dollars. "Constant" dollars are obtained by factoring inflation out of nominal dollar figures. Real discount rates are used with constant dollars and nominal discount rates are used with nominal dollars. Most Air Force economic analyses must be done in constant dollars. After converting any nominal-dollar financial data into constant dollars, a real discount rate of ten percent is used for the analysis in most cases (13:3). AFR 173-15 states, however, that the nominal method, using a prevailing rate, is to be used for all lease *versus* buy decisions (13:3,14). The next section presents some findings from interviews with two Air Force employees who are very familiar with AFR 173-15 and DOD Instruction 7041.3.

<u>Air Force Interviews</u>. Two individuals who work with Air Force economic analyses on a regular basis were interviewed (25; 11). The purpose of these interviews was to gain additional insight into how economic analyses are handled in the Air Force, and to ascertain what problems, if any, were commonly encountered.

Figure 1 shows the coordination process for a typical economic analysis, which originates at a field-level organization such as base civil engineering (for military construction programs). The office of primary responsibility, however, is the corresponding field-level cost analysis organization. The package travels up the chain for coordination and review. At the Major Command level, the originator's (user's) headquarters conducts a substantive review, while the cost analysis organization provides a quality check. A similar coordination and review process takes place at the Air Force level. Next, it goes to the DOD level, and finally an executive summary is forwarded to Congress. Selection of a preferred alternative occurs at each level in the originator's chain of command (11). Congress has the ultimate decision authority based upon its power to control funding. The actual decision will not necessarily be consistent with the results of the economic analysis (25). This should come as no surprise in light of the fact that the economic analysis is only meant to be an input into the final decision. Overriding funding constraints that are only visible at the upper levels of the review chain, for example, may necessitate the selection of a non-recommended alternative.

Problems with economic analyses are frequently encountered during the preparation and review process. The reviewers like to see a documentation package that will facilitate a complete replication of the analysis. Often the documentation package is insufficient for this purpose. Problems also result from packages that are submitted by inexperienced preparers (11). Finally, given the subjective nature of the process, an analysis is extremely vulnerable to biases that may exist in the originator's organization (25).

Two different methods for dealing with qualitative criteria, and subsequently comparing criteria with each other, were reported. An ordinal scale is sometimes applied to the qualitative criteria, and then weighted factors are used to combine the outcomes into single

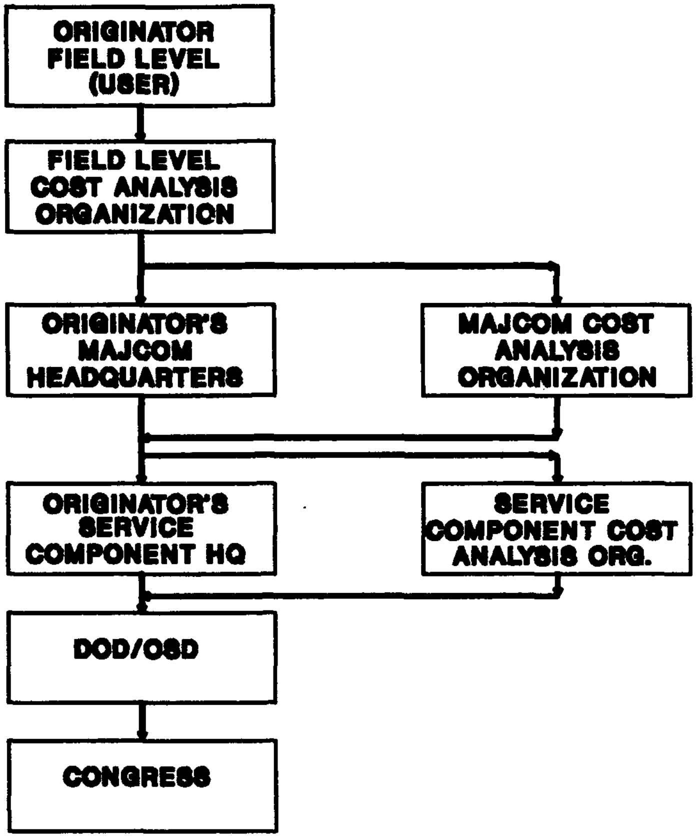

FIGURE 1. Coordination of an Economic Analysis

quantitative scores (25; 11). This is a technically incorrect approach because ordinal data should not be mathematically manipulated in this manner. Many times, side-by-side tables that merely list the advantages and disadvantages of the various alternatives are used (25). The next section discusses capital budgeting in the private sector business community.

Capital Budgeting. A review of capital budgeting practices in the private sector yielded some notable results. Even though much is known about specific areas of the capital budgeting process, such as how to deal with risk, the techniques are not well integrated into actual resource allocation processes (27:6,7). As a result, there is a wide gap between what financial theory says about capital budgeting decisions and how firms actually make those decisions (27:14,15).

> The findings suggest a much more complicated decision process in practice than incorporated in the financially-oriented capital budgeting literature. (27:7)

and

> . . . empirical studies of capital budgeting have shown it to be a somewhat distorted political process far less analytical than the normative literature suggests. (27:8)

Organizational politics, and the reputations of those advocating specific projects are strong factors in the actual decision making process (27:8). One study indicated a reliance on expert judgment over the results of any type of rigorous analysis (8:416). The result, as is evidenced by the following statement, is frequently less than ideal.

> Indeed, carried to its logical conclusion, coalition formation, market share constraints and other multi-objective complications observed in practice probably can be considered to be insurance premia designed to account for the basic lack of predictive accuracy when theoretically based capital budgeting techniques are employed in practice. (27:16)

Two other unfortunate circumstances were reported. Many times decisions are made by people who often do not fully understand the proposals presented to them (27:8). And although capital budgeting techniques are most applicable to strategic decisions, they are often too closely tied to a firm's short-term plans (27:7,10).

Summary. This portion of the literature review answered the first investigative question, "How does the business community in general, and the Air Force specifically, make capital budgeting decisions/conduct economic analyses?" Techniques for objectively considering all of the decision criteria are either inadequate, not used, or both. It was concluded that a more disciplined and systematic process is needed.

Multiple Criterion Decision Making

Capital budgeting and economic analysis decisions can be based on a single quantitative criterion such as cost or net present value. In this situation, the choice of an optimal or "best" solution is not a difficult one, because rating the alternatives is only a matter of mathematically calculating the total cost or net present value. Once each of the alternatives has been rated with respect to the single criterion, selecting the optimal solution requires the decision maker to choose the alternative with the lowest cost or highest net present value.

While capital budgeting and economic analysis are sometimes performed using a single criterion, they are also performed using more than one criterion as a basis for selection of an alternative (7). Today's decision makers are forced to consider not only the financial objective of obtaining the "best" return on dollars invested, they also must consider the political, social, and mission objectives associated with any goal. In deciding which alternative to select to achieve an overall goal, a decision maker normally considers criteria such as performance, risk, and quality in addition to the dollar criterion. The task of selecting an alternative is not hard when the number of alternatives and criteria are small. When these numbers are large, the job of choosing a "best", or even a good, alternative is difficult. Because of this, several multiple criterion decision making (MCDM) tools have been developed to aid the manager (34).

Another reason why MCDM tools are needed to aid the decision maker is that the ratings of the alternatives with respect to each of the criteria usually conflict. Criteria are conflicting if the full satisfaction of one prevents the full satisfaction of another (34). For example, a manager may want to purchase a high-speed and inexpensive computer for the company. In this instance, the high-speed and the inexpensive criteria would most likely conflict, because higher speed computers normally cost more.

A decision involving multiple alternatives and multiple criteria can be represented by the matrix of values presented in Figure 2. For this matrix, the a_1 through a_n represent n different alternatives, the c_1 through c_m represent m different criteria, and the v_{nm} represent the values of each alternative with respect to each criterion. The criteria in this matrix can be defined as conflicting when no alternative dominates all other alternatives on every criterion (34). An alternative dominates all other alternatives when all of the criterion values for that alternative are ranked higher than all of the criterion values for any other alternative.

$$\begin{array}{c|cccc|}
 & c_1 & c_2 & \cdots & c_m \\ \hline
a_1 & v_{11} & v_{12} & \cdots & v_{1m} \\
a_2 & v_{21} & v_{22} & \cdots & v_{2m} \\
\vdots & \vdots & \vdots & \cdots & \\
a_n & v_{n1} & v_{n2} & \cdots & v_{nm} \\ \hline
\end{array}$$

Figure 2. Multiple Criterion Decision Matrix (34)

Examples of decision matrices with non-conflicting and conflicting criteria are presented in Figure 3. The decision matrix on the left in Figure 3 is an example of two criteria that are non-conflicting. If we assume that higher values of the criteria are more important than lower values (maximization) then, the criteria in the left side of Figure 3 are non-conflicting because Alternative 1 dominates Alternative 2 on both criteria. If lower values of the criteria are more important (minimization), then the criteria are also non-conflicting because Alternative 2 now dominates Alternative 1 on both criteria. The right side of Figure 3 is an example of two alternatives with conflicting criteria. This instance is similar to the example of the manager who was attempting to select a computer that was both high-speed and inexpensive. Criterion 1 could represent the speed of the system in milliseconds and Criterion 2 could represent the cost of the computer in dollars. In this example, the speed of Alternative 1 is faster, but this alternative is also more expensive; therefore, the speed and cost criteria for the two alternatives conflict.

$$\begin{array}{cc} & \begin{array}{cc} c_1 & c_2 \end{array} \\ \begin{array}{c} a_1 \\ a_2 \end{array} & \begin{array}{|cc|} \hline 20 & 30 \\ 15 & 20 \\ \hline \end{array} \end{array} \qquad \begin{array}{cc} & \begin{array}{cc} c_1 & c_2 \end{array} \\ \begin{array}{c} a_1 \\ a_2 \end{array} & \begin{array}{|cc|} \hline 10 & 4000 \\ 15 & 2000 \\ \hline \end{array} \end{array}$$

Non-conflicting Criteria   Conflicting Criteria

Figure 3. Decision Matrix Examples

Because the criteria in a MCDM problem often conflict with one another, it is normally not possible to achieve an optimal or "best" solution. In terms of a solution to a MCDM problem, an optimal solution would be an alternative that dominates all other alternatives with respect to all criteria (34). In other words, optimality is only possible when the criteria are non-conflicting. Although problems with conflicting criteria do not have an optimal solution, they may have several solutions that are good solutions. The process of selecting a good solution is called "satisficing" by some authors (34:8).

If the criteria conflict, but the number of criteria and alternative solutions is small, decision makers can sometimes choose an acceptable solution to a problem by weighing all of the alternatives. As the numbers of criteria and alternatives grow, managers can be overwhelmed by the amount of information that they must process in order to select a solution. Several MCDM models and tools have been developed to help the manager rank or rate alternative solutions in a systematic manner (34; 40). Some of the most common MCDM techniques include the following: 1) Single Objective Approach, 2) Goal Programming Approach, 3) Interactive Approach, 4) Compromise Programming Approach, 5) Electre Approach, 6) Parametric Approach, and 7) De Novo Programming Approach (34; 40).

Single Objective Approach. This method of obtaining an acceptable solution optimizes on one of the criteria and uses all of the other criteria as constraints for the problem. The constraints in this optimization problem are assigned a minimum or maximum value that must be achieved in the solution (34:34). For example, an individual purchasing a car may want a car that is inexpensive and luxurious. The individual may think that price is the primary consideration, while luxury is secondary. If this is the case, the individual would minimize the price criterion with some minimum level of luxury (perhaps the individual is willing to accept a car with power windows but no sunroof).

Goal Programming. Goal Programming attempts to select an acceptable solution by minimizing its deviation from the problem solver's stated goals. In Goal Programming, the manager is asked to assign priorities or weights to each of the criteria. The values assigned to the criteria become the target or goal in selecting a solution (34; 40). A criticism of this approach is that the decision makers usually have difficulty specifying *a priori* weights for the stated goals (19).

Interactive Approach. In some situations the problem may be so undefined or so complex that managers may not know which objectives or criteria are most important. This approach requires the managers to state their preferences at the beginning of the search for a solution, and an initial solution is then generated from their judgments. As the search progresses the managers are asked to provide updates to their original judgments in an attempt to narrow in on a preferred solution. The strength of this approach is that it allows managers to learn from the interactive process. The weakness of such an approach is that it requires a great deal of involvement on the part of the decision makers (34). Because of the complex nature of many decisions, this approach has been the subject of several recent articles that tout its importance in MCDM (24; 37; 28).

Compromise Programming. This method of MCDM attempts to select an acceptable solution by geometrically minimizing the distance between possible solutions and an ideal solution (34; 40; 15). The ideal solution is one in which each criterion reaches its individual optimum. Therefore, the ideal solution is not a feasible solution, but it is only used as a point of reference for comparison to alternative feasible solutions. This approach uses several mathematical equations to find the feasible solution that is a minimum distance from the ideal solution (34; 40).

Electre Approach. There are two basic electre approaches: Electre I and Electre II. The purpose behind both approaches is to interactively manage qualitative and discrete alternatives, and allow the decision makers to deal with situations where they must give preferences based upon incomplete knowledge of the problem. Electre is used to select an alternative that is preferred based on the largest number of criteria with the highest rating. At the same time, this alternative must not have an unacceptable level of satisfaction for the remaining criteria (34).

Parametric Approach. At times, the decision maker's preferences may not be available when the analysis process begins. In this case, the problem solver would use the Parametric Approach to narrow the field of potential solutions to a subset which can be presented to the manager for a final selection. When the number of potential solutions is large, the analyst can often eliminate several solutions either mathematically or through heuristic methods (34).

De Novo Programming. In some instances, it may be better to design other alternative systems or solutions for a requirement rather than to select one of the existing alternatives (34; 40). De Novo programming looks at other alternatives in addition to the present ones (34; 40). It also takes a total systems approach to finding a solution for the problem (34).

The techniques in the approaches just described are quantitative in nature, and the decisions that result from using these techniques are commonly based on measurable characteristics of the solution alternatives. When the criteria in a problem are qualitative, the characteristics of the solution alternatives can be difficult to quantify, and the measurement of these characteristics is subjective. Quantification of these characteristics requires the decision makers to assign weights to the criteria and numerical values for the alternatives with respect to the qualitative criteria. The assignment of weights and values can be a difficult task, especially if the number of assignments is large or the decision makers are unfamiliar with the problem at hand. For this reason, most of these approaches are best suited for optimization problems involving alternatives with easily quantified criteria.

The Interactive Approach is perhaps the most appropriate technique for handling qualitative criteria because it allows the decision makers to modify the weights assigned to the criteria and the values assigned to the alternatives (34). The decision makers are not locked into their initial judgments regarding the weights or values, and they are given multiple chances to find an acceptable solution. This makes it easier for managers to choose an initial set of weights for the criteria and numerical values for the alternatives.

Another less common, but more capable, approach to MCDM is the Analytic Hierarchy Process (AHP) (29). This approach provides a method to quantify characteristics of the solution alternatives that are difficult to measure.

<u>The Analytic Hierarchy Process</u>. The AHP is a hierarchical approach for finding a solution to a problem (30). This method establishes ratings and rankings for each of the alternative solutions through a series of pairwise comparisons where each of the alternatives is compared to each of the other alternatives with respect to a higher level goal or criterion. Pairwise comparisons are used to develop a relative rating for two of the alternatives or criteria at a time. The ratings are then mathematically combined to develop an overall rating and ranking for each

of the alternatives. By comparing two alternatives or criteria, the decision maker is able to establish a relative rating for the two items regardless of the units of measure associated with the individual items. Therefore, quantitative criteria, such as dollars, can be compared to qualitative criteria, like product quality. In addition to rating and ranking each of the alternatives, this method provides a means of checking the consistency of the decision maker's preferences. Because of its ability to handle quantitative and qualitative criteria, the AHP is, in some instances, a more appropriate method of solving problems than several of the MCDM techniques that were previously mentioned. The consistency checks feature also adds to the desirability of the AHP relative to the other MCDM methods. A more comprehensive discussion of the AHP is presented next.

The Analytic Hierarchy Process

The capital budgeting and economic analysis techniques used by many organizations do not provide an objective method to include all relevant factors (33:4; 10; 13:9). To perform economic analyses, the US Air Force commonly employs monetary factors such as net present value and internal rate of return (13:9,16). Although the Air Force does consider non-monetary factors in its economic analyses, it does not have a truly systematic approach that includes these factors (10; 13:9). Saaty's AHP is one technique that may allow the Air Force to incorporate non-monetary factors into its analyses in a more scientific fashion (29:1).

The AHP is a multilevel decision aid developed by Thomas Saaty in the 1970's (39:96-97). It allows decision makers to partition large unmanageable problems into smaller parts that are easier to handle. In addition, it provides decision makers with the ability to incorporate intangible as well as tangible criteria into the decision process (36:2). A MCDM problem can be solved with the AHP by first gathering all of the data elements, both tangible and intangible. Once all of the problem data elements are gathered, the AHP can be used to combine the problem elements and derive overall ratings for each of the alternative solutions. From these ratings, management can rank alternative solutions and select the "best" solution, which is the highest rated or ranked solution. In the event that management can choose more than one solution, a simple procedure would be for them to select a number of the highest ranked alternatives. Although this procedure may be simple for a small number of projects, using it for a larger number of projects can be difficult. For this reason, a later section of this chapter will describe a more formal method for selecting multiple alternatives from the AHP ratings.

Another feature of Saaty's process is the capability to check the decision maker's consistency in making comparisons between the importance of multiple criteria (5:6; 29). According to Boucher and MacStravic, the ability to perform consistency checks on the decision maker's judgments is one of the AHP's strongest points in the justification of its use for MCDM problems (5:6).

A detailed description of the steps involved in using the AHP to select a single solution for a MCDM problem is given in the next section. Consistency checks of the decision maker's judgments are described in a later section.

Steps in the Process

Use of the AHP involves the following four steps:

1. Build a decision hierarchy by breaking the general problem into several issues, which are positioned within a hierarchical structure.

2. Gather relational data for the decision criteria. Relational data may already exist in the form of quantitative relationships, or it may be generated through a series of pairwise comparisons of the decision criteria and alternatives.

3. Estimate the relative weights of the decision criteria using the proportional or the *eigenvalue* method.

4. Aggregate the relative weights into a vector that will be used to rank the various decision solutions (39:96-97).

Step 1. This step of the AHP places the general problem at the highest level, specific decision criteria at lower levels, and alternative solutions at the lowest level (39:97). Take, for example, the general problem of selecting a restaurant from among three alternatives. As displayed in Figure 4, the general problem would be placed at the first level of the hierarchy, with factors like price, service, and food quality positioned at the second level. Restaurant alternatives would be placed at the third level.

Step 2. This step of the process gathers relational data on the criteria and alternatives in a MCDM problem. This data may already exist as a result of quantitative measurements of the alternatives, or it may be generated through pairwise comparisons (39:96). In the restaurant example, there is no preexisting relational data that indicates the importance of price, service, and food quality to the general problem. Because these data do not exist, they could be generated by the decision maker through a series of pairwise comparisons. In this case, each of the criteri- would be compared two at a time for their relative importance in the solution of the general problem. Saaty suggests that decision makers use a ratio scale (31:407) that ranges from 0 to 9, to assign a relative weight to each criterion (29:18). This scale allows a decision maker to assign a relative importance, to each criterion, in the indicated range. For instance, a rating of 2 signifies that a criterion is twice as important as another criterion. One author recommends operationalizing these numbers for decision makers by attaching a verbal description to some of the ratings as shown in Table 1 (33:5).

The results of one possible combination of pairwise comparisons regarding price, service, and food quality are shown in Table 2. The comparisons are organized as a matrix. A pairwise comparison matrix is made up of comparisons between the criteria in each row of the matrix and

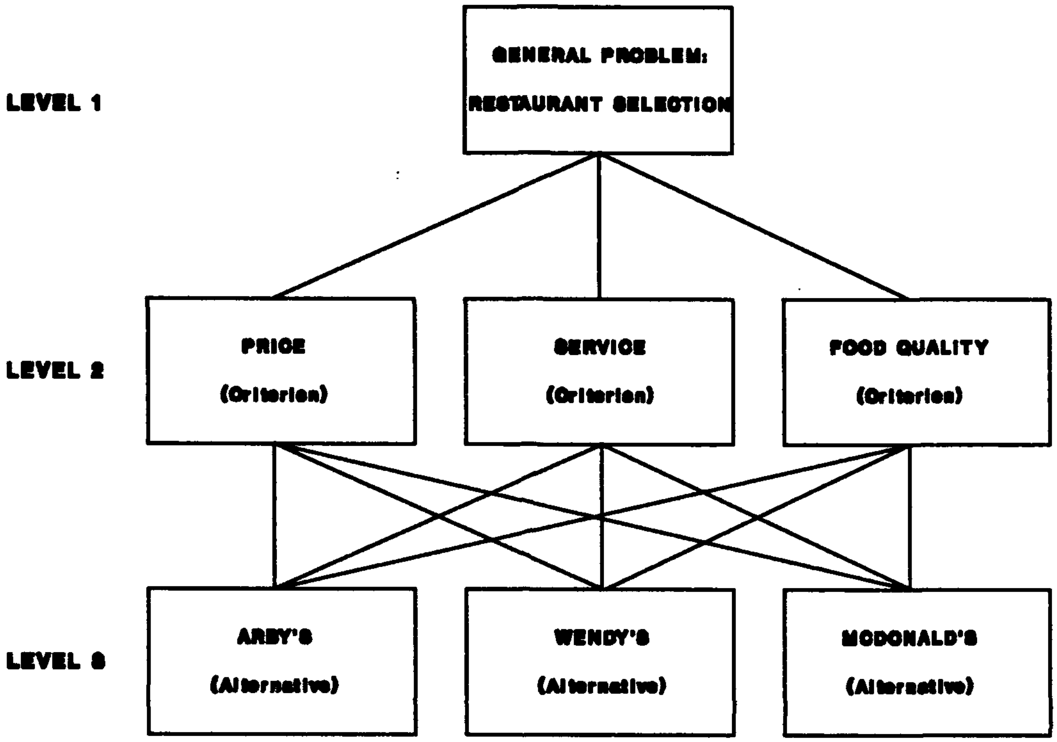

Figure 4. Restaurant Selection Hierarchy

TABLE 1 (33:5)

PAIRWISE COMPARISON MEASUREMENT SCALE

Verbal Judgement	Numeric Rating
Extremely Favored	9
Very Strongly Favored	7
Strongly Favored	5
Moderately Favored	3
Equal	1
Moderately Disfavored	1/3
Strongly Disfavored	1/5
Very Strongly Disfavored	1/7
Extremely Disfavored	1/9

the criteria in each column of the matrix. For example, the price criterion in the first row of the matrix in Table 2 is compared to the price, service, and food quality criteria in the matrix columns. In this instance, the first pairwise comparison would be between price in the first row and price in the first column. The pairwise comparison of the price row to the price column will always result in a rating of 1, because a comparison between two identical criteria is always equal. This relationship is true for every comparison along the main diagonal of the pairwise comparison matrix, because these ratings are a result of criteria that are compared to themselves.

TABLE 2

PAIRWISE COMPARISONS OF CRITERIA

Criterion	Price	Service	Food Quality
Price	1	3	5
Service	1/3	1	2
Food Quality	1/5	1/2	1

In another comparison presented in Table 2, the price criterion in the first row of the matrix is compared to the service criterion in the second column. The result of the price to service comparison was a rating of 3, which means that price was deemed "moderately favored" to service. This comparison also suggests that price is three times as important as service. Consequently, consistency demands that a comparison between service in the second row and price in the first column have a rating of 1/3, which indicates that service is "moderately disfavored" to price. In every instance, consistency requires an inverse relationship between the rating of one pairwise comparison and the rating of a reverse comparison. Because of this inverse relationship, the decision maker is only required to enter the ratings for the pairwise comparisons in the upper or lower triangle of the matrix (29). This reduces the number of comparisons required of the decision maker. The pairwise comparisons for the remaining triangle of the matrix are normally calculated from the comparisons in the input triangle (29). Several computer packages, such as Expert Choice (12) and Automan (26), are available, which will automatically perform such calculations.

At the second level of the hierarchy shown in Figure 4, one matrix of pairwise comparisons is required in which the rows and columns represent each criterion. At the third level (the bottom level), one matrix of pairwise comparisons is usually required for each criterion.

At the third level, the price of the meal was quantified in dollars; therefore, it was not necessary to use pairwise comparisons to generate ranking data. Each restaurant was compared according to the average price of a meal as shown in Table 3.

TABLE 3

AVERAGE PRICE OF A MEAL

Arby's	Wendy's	McDonald's
$5	$4	$3

Data for the service and food quality at each restaurant would need to be generated through a series of pairwise comparisons similar to the earlier comparisons in Table 2. In this case, the decision maker was asked to compare each restaurant on the quality of service and food. An example of possible pairwise comparisons for the service and food quality of each restaurant is displayed in Table 4. The matrix of ratings for the quality of service is shown in the upper portion of Table 4, while the ratings matrix for the quality of food at each establishment is presented in the lower portion of the table.

Step 3. This step of the AHP assigns relative weights to the criteria and alternatives by using either the proportional or the *eigenvalue* method (39:96). The proportional method assigns weights based on quantitative ranking data, such as the price data in Table 3. The *eigenvalue* method uses pairwise comparison data, such as the data in Tables 2 and 4, to assign the weights.

TABLE 4

PAIRWISE COMPARISON OF ALTERNATIVES

SERVICE	Arby's	Wendy's	McDonald's
Arby's	1	1/3	1/5
Wendy's	3	1	1/2
McDonald's	5	2	1

FOOD QUALITY	Arby's	Wendy's	McDonald's
Arby's	1	6	4
Wendy's	1/6	1	3
McDonald's	1/4	1/3	1

Proportional Method. The proportional method is used to assign weights to data that are in units such as dollars, which are directly quantifiable. This method assigns values according to the amount each alternative contributes to the sum of the values of all of the alternatives for a particular criterion (33:7). The algebraic formula for proportion is denoted by

$$p_i = v_i/t \tag{2}$$

where p_i is proportion, v_i is alternative value, and t is total of all alternative values for a particular criterion. For instance, if two alternatives were compared on total dollar return on investment, with Alternative A returning \$1 and Alternative B returning \$2, then Alternative B would be the preferred alternative because it returns more. To calculate the proportion for these alternatives, the decision maker would first calculate the total dollar value of the two alternatives by summing all of the dollar values as follows: $t = (1 + 2) = 3$. Using the total and Equation 2, the proportion for Alternative A could be found through the calculation: $p_i = 1/3 = 0.333$. The proportion for Alternative B could be calculated in a similar manner resulting in a proportion of 0.667.

In the restaurant example, the ratings for each of the alternatives based upon price cannot be directly calculated using Equation 2, because lower dollar values are preferred to higher dollar values. If Equation 2 were used to calculate the weights for each alternative, then the higher priced alternatives would be assigned a higher rating. Therefore, to calculate the weights of several alternatives where smaller amounts of a value are preferred, the value of each alternative must be inverted. The revised equation would be the following:

$$p_i = (1/v_i) \;/ \sum_{i=1}^{k} (1/v_i) \tag{3}$$

where p_i is proportion, v_i is alternative value, and k is the total number of alternatives.

For example, to calculate the proportion for the Arby's price alternative in Table 3, the decision maker would first calculate the value of the total by summing the inverted dollar values for the price criterion as follows: $t = (1/5 + 1/4 + 1/3) = 47/60$. Using this total and Equation 3, the proportion for the Arby's price alternative could be found through the calculation: $p_1 = (1/5)/(47/60) = 0.255$. The results of proportion calculations for all of the price alternatives are presented in Table 5. Because McDonald's was the least expensive restaurant in this example, it was assigned the highest proportional rating. Each of the ratings reflect the relative importance of each restaurant on the price criterion. A higher rating indicates that the restaurant is preferred to restaurants with a lower rating. The sum of all of the ratings should be equal to one because each rating indicates the portion that each alternative contributes to the "whole" price criterion.

TABLE 5

ALTERNATIVE PRICE PROPORTIONS

Arby's	Wendy's	McDonald's
0.255	0.319	0.426

Eigenvalue Method. The *eigenvalue* method is a mathematical technique that is used to calculate relative weights from the pairwise comparison data (29:258-259). Saaty suggests that in theory the actual weights of each criterion or alternative may be known (29:23). In this case, the pairwise comparison matrix would be defined as follows:

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \vdots & \vdots & & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{bmatrix} \tag{4}$$

where n is the number of rows or columns in the square matrix, w_i is the weight of each criterion or alternative for i = 1 to n and A is the pairwise matrix. Equation 4 can be a pairwise comparison matrix for n criteria or alternatives. Suppose that Equation 4 was a comparison of various criteria. As in all pairwise comparisons, the value found in a particular row and column is the weight of that row's criterion in relation to that column's criterion. For instance, the value of the second row and first column is the ratio w_2/w_1, which indicates the relative importance of the criterion in the second row to the criterion in the *first* column. Finding the weights of each of the criteria with respect to all other criteria requires estimation of the characteristic values or *eigenvalues* (29). *Eigenvalues* are a special group of numbers which are related to the matrix of weights in Equation 4 (1:179). The vector of relative weights for several criteria are estimated using *eigenvalues* and the matrix of pairwise weights, matrix A. Given that the weights of each of the criteria are deterministic, the relative weights of each criterion would be determined by solving the equation:

$$A \cdot W = n \cdot W \tag{5}$$

where A is the matrix of actual pairwise weights, W is the right *eigenvector* of actual relative weights for matrix A, and n is the eigenvalue for matrix A (39:98-99).

<u>Estimating Weights</u>. Because the decision maker does *not* know the actual weights contained in matrix A, Saaty suggests that the following equation be used to estimate the relative weights:

$$\hat{A} \cdot \hat{W} = \Lambda_{max} \cdot \hat{W} \tag{6}$$

where $\hat{A}$ is the matrix of pairwise comparisons, $\hat{W}$ is the estimate of relative weights, and Λ_{max} is the largest *eigenvalue* of $\hat{A}$ (29:51). The exact solution for $\hat{W}$ in Equation 6 is calculated by raising $\hat{A}$ to arbitrarily large powers and dividing the sum of each row by the sum of all of the elements in the matrix (29:20). Because the exact computation of $\hat{W}$ requires a relatively powerful computer (29:19), Saaty presents four techniques that provide an approximation of $\hat{W}$ (29:20; 30:80-81). Saaty suggests that two of the methods provide the most accurate approximation of $\hat{W}$ (29:20). The first method normalizes the $\hat{A}$ matrix by dividing each element of the matrix by its respective column total (30:80-81). Once the matrix is normalized, each row is averaged to determine the elements of the relative weight vector $\hat{W}$ (30:81). In the second method, the n elements in each row are multiplied and the nth root of each product is found. The resulting vector of roots is then normalized by dividing each element of the vector by the total of all of the elements in the vector (29:19). This method provides the closest approximation of $\hat{W}$ (29:19-21). The results of applying the second method to the pairwise comparison of the criteria in Table 2 are shown in Table 6. This method was also applied to the pairwise comparison of the alternatives in Table 4 and the results are presented in Table 7.

TABLE 6

EIGENVECTOR FOR PAIRWISE COMPARISONS OF THE CRITERIA

Price	Service	Food Quality
.648	.230	.122

TABLE 7

EIGENVECTORS FOR PAIRWISE COMPARISONS OF THE ALTERNATIVES

Criterion	Arby's	Wendy's	McDonald's
Service	.109	.309	.582
Food Quality	.701	.193	.106

<u>Step 4</u>. This step of the AHP aggregates the relative weights of all of the criteria into a single vector, which reflects the relative ranking of the decision alternatives (39:96). The vector of ratings for the alternatives at the lowest level of the hierarchy is determined by a series of matrix multiplications beginning at the second level and ending at the lowest level of the hierarchy. The formula for calculating the ratings of the alternatives is as follows:

$$C[1,k] = \prod_{i=2}^{k} B_i \tag{7}$$

where C[1,k] is the vector of weights for the alternatives at level k with respect to level 1, B_i is the n_{i-1}-by-n_i matrix composed of $\hat{W}$ vectors, and n_i is the number of criteria or alternatives at each level i (39:99).

In the restaurant example, C[1,k] is a vector of weights for the alternatives at level 3 with respect to level 2, and B_i is the n_i-by-n_{i-1} matrix with n_i equal to 3 at the third level, and n_{i-1} equal to 3 at the second level. In this example there are two B_i matrices; one is the matrix of criteria weights contained in Table 6, and the other is a matrix composed of the weights of the alternatives contained in Tables 5 and 7. C[1,k] is calculated by the following matrix multiplication using Equation 7:

$$[.648 \ .230 \ .122] \ * \begin{bmatrix} .255 & .319 & .426 \\ .109 & .309 & .582 \\ .701 & .193 & .106 \end{bmatrix}$$

Table 8 shows the results of the application of this step to the relative weights. The ratings for the alternatives in Table 8 were used to assign a rank to each of the alternatives. In this example, McDonald's was considered to be the "best" restaurant based on the decision makers' preferences for the stated criteria.

TABLE 8

OVERALL RATINGS AND RANKINGS FOR THE RESTAURANT EXAMPLE

Alternative	Rating	Rank
Arby's	.276	3
Wendy's	.301	2
McDonald's	.423	1

Selecting Multiple Alternatives

The discussion in the previous section was primarily concerned with the procedures for generating ratings for each of several alternative solutions to a MCDM problem. After the ratings are established, it is simple for management to select a single "best" solution, which is the highest rated alternative.

In some cases management may be able to choose more than one alternative. If the resources were available to implement all of the alternatives, then the choice would be between selecting all of the alternatives and selecting a subset of the alternatives. In this case, the choice would not be a difficult one, because there is no resource limitation. If resources are not available to implement all of the alternatives, then the decision makers would be forced to choose a subset of the alternatives. In this limited situation, it may not be difficult to select a small number of the top rated alternatives. Management may simply weigh the various combinations of alternatives and select one good combination.

The selection process becomes more difficult when the number of alternatives is large. When the number of alternatives is large, the number of combinations can be enormous. Because of this problem, another method for selecting multiple alternatives is required. One possible method would be to use integer linear programming to choose the combination of alternatives that would give the largest combined rating (16). Linear programming is a mathematical technique that can be used to decide how to best allocate a limited pool of resources among several alternatives (21; 38). Integer linear programming is a subset of linear programming where the decision variables can only be integer valued. In integer programming, the values in the solution indicate how many times each alternative should be implemented. For example, the results of using integer linear programming on the AHP ratings for two alternatives could be

Alternative 1	Alternative 2
3	1

In this example, the results indicate that Alternative 1 should be implemented three times and Alternative 2 should be implemented one time.

One problem with using integer programming to select the best combination of alternatives from the AHP ratings is that the solution can be any integer value greater than zero. In many situations, it is normally not possible to implement a particular alternative more than one time. For instance, if the solution suggested that the Air Force remodel a building, then it would not be wise to remodel more than once. Therefore, the solutions for integer linear programming should be limited to zeros and ones. Zero-one programming is a subset of integer linear programming that restricts the values of the possible solutions to a zero or a one. The result of such a restriction in a linear programming problem is that an alternative solution can be either chosen or not chosen. A zero in the linear programming solution set indicates that the alternative should not be selected, while a one suggests that the alternative should be chosen. As in integer linear programming, no fractional or partial alternatives can be selected (38).

An important requirement in using zero-one programming to select a "best" combination of alternatives is that the ratings provided by the AHP must be additive. In other words, the sum of one combination of ratings must be directly comparable with the sum of another combination. Assuming that the ratings are additive, then combinations of ratings can be compared and a "best" combination can be chosen using zero-one programming.

There are a number of different types of scales that can be used to rank the alternatives in a MCDM problem. Four scales that are often mentioned in the literature are 1) nominal scales, 2) ordinal scales, 3) interval scales, and 4) ratio scales. Of these four, only data measured on interval and ratio scales can be added (29:223).

Nominal Scales. This type of scale places the data into classes or groups (34). Nominal scales do not provide a good means to rank the groups of data. Although numbers can be assigned to the data classes, no meaningful mathematical transformations could be performed on the classification numbers. For example, undergraduate students could be classified according to their study major. In this example, numbers could be assigned to each of the classifications, but the numbers would only be useful as labels for the students. If business majors were assigned a one and engineering majors were assigned a two, then the sum of two business majors would not equal an engineering major.

Ordinal Scales. These scales are exclusively used for ranking (29; 34). For instance, in a horse race, horses are assigned a ranking position at the end of the race. This ranking marks what position the horses finished, but it does not indicate the relative difference between the horses' finishing times.

Interval Scales. This type of scale not only has order like an ordinal scale, but it also has constant units of measurement (29; 34). The Fahrenheit temperature scale is a typical example of an interval scale (34). In this instance, degrees in Fahrenheit are uniformly measured constant units, which indicate a specific difference in degrees between two temperatures. The constant units of interval scales allow them to be used for certain mathematical transformations, such as addition and subtraction. These mathematical operations are only meaningful when the measurements are derived from the same scale. For instance, measurements of temperature in degrees Fahrenheit and temperature in degrees Celsius can not be added because they are derived from different scales. One weakness of this type of scale is that there is not a natural zero point (34). Because the zero points of the Fahrenheit and Celsius scales are artificially chosen points, a temperature of 50 degrees cannot be said to be twice as hot as 25 degrees.

Ratio Scales. The principal difference between ratio scales and interval scales is that ratio scales have a natural zero point (29; 34). The zero point of ratio scales allows them to be used for multiplication and division as well (29). Examples of measurements on a ratio scale include those involving length and speed. Another example of a ratio scale of measurement is Saaty's 0 to 9 scale used in making pairwise comparisons (20:1338-1339). In rating alternatives or criteria on this scale, the AHP implicitly assumes that the decision makers have the ability to assign such weights based on their experience or actual measurement.

The AHP provides an *eigenvector* of ratings, which are used to rank several alternatives on a ratio scale (29; 31:407). According to Saaty

> the AHP utilizes the notion of priority to perform multicriteria ratio scale measurement in a hierarchy or network . . . the process of weighting and adding ratio scales leads to a ratio scale ranking of the alternatives. (31:407)

The vector of ratings in a typical AHP problem is based on pairwise comparison data and quantitative data measured on ratio scales. The AHP appears to transform this data into ratings on a single ratio scale of measurement that indicates the relative preference of the solutions to each other.

The AHP and Zero-One Programming. Project selection using the AHP and zero-one programming is a relatively new concept. As stated earlier, additivity of the AHP ratings is a requirement for the use of zero-one programming in the selection of multiple solution alternatives in a MCDM problem. Ratings of alternatives established by the AHP are measured on a ratio scale that ranges from 0.0 to 1.0 (29). The ratings for each of the alternatives are like pieces of a pie which make up a whole. In this case, the whole pie is composed of the total rating of 1.0, and the sum of the ratings for all of the alternatives is 1.0. Because these ratings are measured on a ratio scale, they can be added to form larger ratings, which can be compared with other ratings on the same scale. In effect, two or more pieces of pie are added together and then compared to another piece of pie or pieces of pie.

The ratings generated by the AHP for a set of alternatives can be used in a zero-one programming problem to obtain an optimal combination of alternative solutions. Mathematically a zero-one programming problem is denoted by the following set of equations:

$$\text{Maximize} \qquad f = \sum_{j=1}^{n} c_j x_j \tag{8}$$

$$\text{subject to} \qquad \sum_{j=1}^{n} a_{ij} x_j \leq \text{ or } \geq r_i$$

$$i = 1, 2, \ldots, m$$

$$x_j = 0 \text{ or } 1$$

where x_j are the numbers of times that alternatives should be implemented, c_j are the values of the ratings provided by the AHP, a_{ij} are the values of the individual criteria for a given alternative j and criterion i, r_i are the constraints of the individual criteria, n is the number of alternatives, and m is the number of constraints. Equation 8 is called the "objective function" in linear programming problems (38). The a_{ij} values in a problem of this nature could reflect either resource or policy constraints on the solution. An example of a resource constraint would be the cost of implementing each alternative, x_j, or the number of labor hours required to implement each alternative. In this example, r_i would be the number of dollars available or the number of labor hours available. Policy constraints on a decision would be limitations that require the solution to select specific combinations of the alternatives for implementation. For instance, $x_1 - x_2 = 0$ is a policy constraint on two alternatives that requires either none or both of the projects to be implemented. In this case, the values of a_1, a_2, and r_1 are 1, -1, and 0, respectively.

The Branch and Bound Method of Zero-One Programming. One technique for finding the solution to a zero-one programming problem is the "branch and bound" method. This technique searches the set of possible solutions and divides the set into subsets of solutions, thus narrowing the set of possible solutions until a single solution can be found (38). It uses a tree structure similar to the one in the AHP to search the set of possible solutions. The number of possible solutions to a zero-one programming problem is two to the nth power, where n is the number of alternatives. For example, if n is three, then there are eight possible solutions. The branch and bound method eliminates some of these possible solutions by calculating partial solutions. Partial solutions are solutions in which some of the x_j values are already assigned. The x_j values which are not fixed are called "free." (38) A "completion" to the branch occurs when all of the free x_j's are assigned a value of zero or one (38:421).

The algorithm for solving a zero-one programming problem using the branch and bound method is as follows:

Step 1. Generate a lower bound f_L on the maximum value of the objective function. This can be done by using the solution x_j equals zero for all j values. The lower bound becomes the top node in a tree structure (38).

Step 2. Select a free variable, such as x_k, and use it to generate two branches, one where x_k equals zero and another where x_k equals one. The value of x_k then becomes fixed on each of these branches (38).

Step 3. For each new partial solution, denoted by nodes at the ends of the two branches, compute an upper bound on the maximum value of the objective function, f_U (38).

Step 4. Select the most recently created partial solution. This branch of the tree can be eliminated from further consideration at this point if 1) $f_U < f_L$, 2) there are no feasible completions for this branch, 3) there are no free variables, or 4) the upper-bound calculation, f_U, generates a feasible completion. If condition 4 is met and $f_U > f_L$, then replace f_L with the value of f_U, store the values of the x_j's as the current solution (38). If a branch of the tree has been eliminated and there are remaining partial solutions, then repeat Step 4 (38).

Step 5. If there are no remaining partial solutions, then the current solution becomes the optimal solution. Otherwise, go to Step 2 (38).

The appendix is an example branch and bound problem involving three military construction projects.

The calculations in a branch and bound problem can be tedious, especially when the number of alternatives is large. There are several software packages that can be used to perform zero-one programming (9; 32). Quantitative Systems for Business (QSB), and Linear Interactive and Discrete Optimizer (LINDO) are two commonly used packages that are available at some government installations. The use of packages like QSB or LINDO can significantly decrease the amount of time required to find a solution to problems that require the selection of multiple alternatives (9; 32).

Consistency Ratios

When decision makers enter their judgments regarding the importance of one criterion over another, they are often inconsistent. For instance, when a decision maker is asked to compare the importance of price to service and then service to food quality, the decision maker may believe that price is twice as important as service, and that service is twice as important as food quality. In addition, the decision maker may believe that food quality is twice as important as price. In mathematical terms, this set of judgments could be presented by the following relationships:

$$P>S \text{ and } S>F \text{ and } F>P \tag{9}$$

where P is price, S is service, and F is food quality. This set of judgments would be logically inconsistent by the Transitive Property of Inequalities (29:73).

Because of the possibility that the decision makers could be inconsistent in making judgments regarding the relative importance of criteria, Saaty developed a technique for assessing the consistency of the judgments. His technique involves a comparison between Λ_{max}, which is the maximum or principle eigenvalue, and n, which is the number of criteria in the pairwise comparison matrix (29:21). The maximum eigenvalue, Λ_{max}, can be calculated by using the following steps:

1. Multiply the matrix of pairwise comparisons on the right by the estimated solution vector to obtain a new vector.

2. Divide each component of the new vector by its corresponding component in the estimated solution vector to obtain another vector.

3. Add the components of the vector obtained in step 2 and divide this sum by the number of components in the vector to obtain an estimate of the maximum eigenvalue, Λ_{max} (29:21).

Saaty demonstrates that the value of Λ_{max} is greater than the value of n (29). He also suggests that the decision maker's judgments are more consistent as the value of Λ_{max} approaches the value of n (29:21). Saaty recommends that the following formula be used to calculate a consistency index (CI) for the pairwise comparison matrix:

$$CI = (\Lambda_{max} - n)/(n-1) \tag{10}$$

where Λ_{max} is the maximum eigenvalue and n is the number of criteria in the pairwise comparison matrix (29). The CI can then be used in the following formula to calculate a consistency ratio (CR):

$$CR = (CI/ACI)*100 \tag{11}$$

where CI is the consistency index calculated in Equation 10 and ACI is the average index of randomly generated weights (29; 39). The ACI was generated for matrices of order 1 to 15 during experiments at the Oak Ridge National Laboratory and the Wharton School (29). A complete table of the 15 ACI values can be found by referring to page 21 of Saaty's book (29). According to Saaty, a CR of 10 percent or less is an acceptable level of consistency (29:21). The 10 percent level of consistency is statistically based, and is the result of the empirical studies conducted at the Oak Ridge National Laboratory and the Wharton School (29:21,62).

Example AHP Application

One example described by Stout and his colleagues involved a manufacturer's decision to invest in one of three alternatives of new manufacturing technology (33:4). The engineering department in this hypothetical firm presented the following three investment alternatives: one computer numerically controlled (CNC) matching center and two flexible manufacturing systems FMS-1 and FMS-2.

A computer implementation of the AHP called "Expert Choice" was used to perform the analysis on this example application (39:99). Although there are other software implementations of the AHP (e.g., "Automan"), Expert Choice allows the decision makers to numerically, verbally, or graphically express their preferences for a particular alternative or criterion (33:5; 5; 12). In addition, the sensitivity analysis features of Expert Choice give the decision makers the capability to answer "what-if" questions about the effects of various levels of criterion importance (12).

Use of Expert Choice requires a four-step process that is similar to manual application of the AHP. The four steps are as follows (33:5):

1. Specifying the model. In this step, project criteria and alternatives were identified and organized. Expert Choice was used to construct the model specification hierarchy as displayed in Figure 5. The overall goal of the firm was to select one of the automated manufacturing investment alternatives (33:4-5). This selection example

included the following three categories: 1) Financial, 2) Non-financial Quantitative, and 3) Qualitative. As shown in Figure 5, each model category had several criteria, which were used to assess all of the alternatives. The alternatives were placed at the lowest level of the hierarchy displayed in Figure 5.

2. Gathering category and criterion weights. In this step, data indicating the relative weights of the categories and criteria was gathered through a series of pairwise comparisons. Expert Choice uses a scale, ranging from 1.0 to 9.9, which is similar to the one mentioned in Table 1; however, Expert Choice requires the decision maker to invert the alternatives when entering preference values ranging from 0.1 to 1.0 (12). For instance, a pairwise comparison with apples one-half as important as oranges, would become a pairwise comparison of oranges to apples, with oranges twice as important as apples.

Table 9 shows an example of pairwise comparisons for the categories in Figure 5. In theory, because Table 9 is a 3 by 3 matrix, there should be 9 pairwise comparisons required (33:5). However, the comparisons along the main diagonal always result in a value of 1, and comparisons in the lower triangle of the matrix are not required because the matrix is symmetric. Consequently, the comparisons along the main diagonal and lower triangle of the matrix are not required by Expert Choice. The symmetric nature of the pairwise matrix allows Expert Choice to calculate the values in the lower triangle from the ones in the upper triangle (33:6). The last column of Table 9 contains the weights for each of the criteria with respect to the overall goal of selecting an investment. Expert Choice classifies these weights as "global" because they are calculated with respect to the overall goal at the highest level of the hierarchy. In every instance the sum of the category weights will equal the weight of the top level goal, which is 1.0.

Examples of pairwise comparison data for the criteria in Figure 5 are presented in Table 10. Each of the criteria in Table 10 has a global

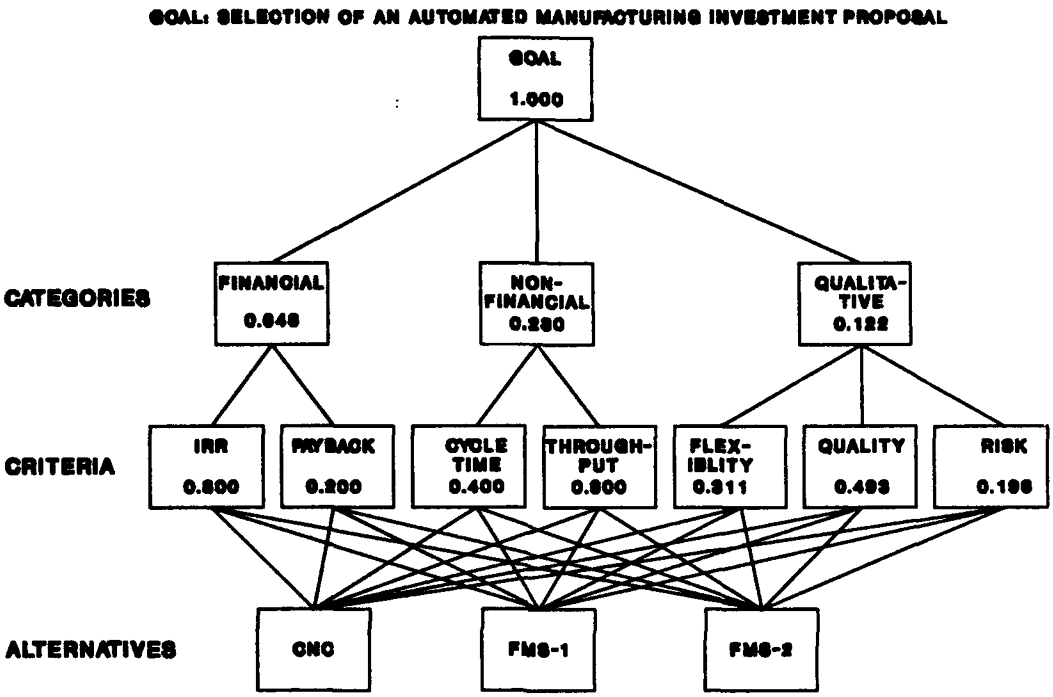

Figure 5. Automated Manufacturing Selection Hierarchy

TABLE 9

PAIRWISE COMPARISONS FOR CATEGORIES (33:6)

Category	Financial	Non-financial	Qualitative	Weights
Financial		3	5	0.648
Quantitative			2	0.230
Qualitative				0.122
				1.000

weight with respect to the overall goal and a local weight with respect to its corresponding category. Expert Choice always classifies weights as global when they are determined with respect to the goal at the highest level of the hierarchy, and local when they are determined with respect to the next highest level in the hierarchy (12).

TABLE 10

PAIRWISE COMPARISONS FOR CRITERIA (33:6)

FINANCIAL CRITERIA

Criterion	IRR	Payback	(Local) Criterion Weights	(Global) Criterion Weights
Internal Rate of Return (IRR)		4	0.800	0.518
Payback			0.200	0.130
			1.000	0.648

NON-FINANCIAL CRITERIA

Criterion	Throughput	Cycle Time	(Local) Criterion Weights	(Global) Criterion Weights
Throughput		1.5	0.600	0.138
Cycle Time			0.400	0.092
			1.000	0.230

QUALITATIVE CRITERIA

Criterion	Flexibility	Quality	Risk	(Local) Criterion Weights	(Global) Criterion Weights
Flexibility		0.5	2	0.311	0.038
Quality			2	0.493	0.060
Risk				0.196	0.024
				1.000	0.122

3. Rating investment alternatives. This step involves rating the alternatives with regard to the criteria (33:6). The rating data can be assembled through pairwise comparisons or from estimated performance data. Table 11 presents some hypothetical pairwise comparison data for the qualitative criteria. The estimated performance data are shown in Table 12.

After all of the data shown in Tables 9 through 12 are input into the computer, Expert Choice calculates the ratings by criterion (12). The results of these calculations are displayed in Table 13. Each of these ratings is a local rating, which reflects how each of the

TABLE 11

PAIRWISE COMPARISONS FOR QUALITATIVE CRITERIA (33:7)

FLEXIBILITY CRITERION

	CNC	FMS-1	FMS-2
CNC		0.5	0.2
FMS-1			0.5
FMS-2			

QUALITY CRITERION

	CNC	FMS-1	FMS-2
CNC		0.5	0.333
FMS-1			1
FMS-2			

RISK CRITERION

	CNC	FMS-1	FMS-2
CNC		6	8
FMS-1			3
FMS-2			

TABLE 12

PERFORMANCE DATA (33:7)

Criterion	CNC	FMS-1	FMS-2
IRR (%)	25	23	22
Payback (months)	36	48	60
Throughput (units/hour)	10	25	60
Cycle Time (hours)	24	16	12

TABLE 13

RATINGS BY CRITERION (33:7)

Criterion	CNC	FMS-1	FMS-2
IRR	0.357	0.329	0.314
Payback	0.426	0.319	0.255
Throughput	0.105	0.263	0.632
Cycle Time	0.222	0.333	0.444
Flexibility	0.128	0.276	0.595
Quality	0.169	0.387	0.443
Risk	0.761	0.166	0.073

alternatives ranks on an individual criterion. For example, ratings 0.357, 0.329, and 0.314 for the IRR criterion indicate that CNC ranks the highest on this criterion, with FMS-1 and FMS-2, ranking second and third, respectively.

4. Ranking investments. In addition to the ratings by criterion, Expert Choice also provides an overall rating for each of the alternatives (12). The local ratings for each of the criteria are transformed into global ratings for each of the criteria, and then the global ratings are added to form an overall rating of the projects. The projects can be ranked from these ratings with the highest ratings receiving the highest ranks. Table 14 shows the ratings and ranks of each project in the example.

TABLE 14

RATINGS AND RANKS OF ALTERNATIVES

Alternative	Rating	Rank
FMS-2	0.375	1
FMS-1	0.316	2
CNC	0.309	3

Applications of the AHP

Since the AHP was developed, it has been applied to a large number of fields. Vargas lists over 40 separate applications ranging from economic/management problems to technological problems (36:5). In addition to these applications, Saaty has published several books, which provide the reader with in-depth coverage of the AHP and its applications (30; 29).

Several Air Force personnel have reported using the AHP for actual economic analyses. Mr. David Graham, formerly of the Air Force Cost Analysis Agency, and Capt Susan Aungst, from the Joint Studies Group at Tactical Air Command Headquarters have used the AHP on economic analysis projects relating to their specific fields (17; 2). Capt Aungst has completed the first phase of a planned two-phase project that compares the benefits (performance, reliability, maintainability, etc.) derived from different modifications that have been proposed for various aircraft in the inventory of the U.S. tactical air forces. Phase I involved the use of Expert Choice to rank the proposed modifications strictly according to their overall benefit value. In Phase II, she intends to include the dollar costs of each modification, along with the acknowledgement that there is a limited budget. She plans to employ zero-one integer linear programming to determine the best subset of alternatives (2). Mr Graham used the AHP to generate a rank-ordering for Military Airlift Command's Integrated Scheduling and Internetting program, which was subject to the Major Automated Information Systems Review Council. He used a technique that generated separate outputs for costs and for benefits. These costs and benefits were then combined into cost/benefit ratios for each alternative (18).

Criticisms of the AHP

Bernhard and Canada have criticized Saaty's cost/benefit ratios method. This approach uses two separate hierarchies to produce two output vectors, one for the costs, and one for the benefits. A simple cost/benefit ratio is then formed for each alternative from the respective elements of the two vectors. Bernhard and Canada state that, when both the costs and the benefits are measured in purely monetary units (or some other common unit), these ratios do not necessarily provide the decision maker with the optimal solution (3:57,58). They suggest an alternative to forming simple cost/benefit ratios from the AHP output vectors. Their method involves the elements of the AHP output vectors in a mathematical formula that is used to compare alternatives two at a time in a specified order until all of the alternatives have been evaluated. In an example where dollars are used as the common unit, their method yields the alternative with the highest net monetary gain, whereas Saaty's method yields just the opposite (3:59,60).

Bernhard's and Canada's presentation is mathematically sound as far as it goes; however, there are two counter-arguments that should be considered. First, it is generally inappropriate to separate into costs and benefits any criterion that can be measured in common units (4). The two quantities should be added together to yield a single quantity for any given alternative. This single quantity should be treated consistently across all of the alternatives as either a cost or a benefit. With this approach, a single-hierarchy AHP analysis could be used on the example referred to above to yield results that are consistent with those produced by Bernhard's and Canada's method. The second counter-argument is that the integrity of Bernhard's and Canada's mathematical formula depends on the commonality of the units involved. Their formula involves addition, which only makes sense for common units (3:59). Bernhard and Canada imply that their method is generalizable to the situation where the criteria are expressed in incompatible units (3:58). This clearly is not true.

Boucher and MacStravic have claimed that the output vector from a single-hierarchy AHP analysis results in an incorrect ordering of the alternatives (5:3). They propose that the correct ranking of alternatives, for a problem with all quantifiable criteria, is obtained through a direct combining of the scores of the various alternatives with respect to each criterion, and the weight assigned to that criterion (the weighted factors approach) (5:13). This popular method incorrectly assumes that the units of the various criteria are compatible with each other. Based on this incorrect assumption, they assert that the AHP matrices of the alternatives with respect to the criteria should contain absolute scores instead of pairwise ratios (5:15). This leads to (incorrect) results that are consistent with the direct method (5:17).

Another criticism offered by Boucher and MacStravic is that the pairwise comparison process for determining relative weights of the various criteria is too ambiguous (5:6). They suggest an approach where a separate criteria matrix pertaining to each individual alternative is generated (5:18). This allows for consideration of the relative importance of each criteria at the specific levels associated with each individual alternative. This approach has some merit. It would be especially beneficial in problems involving qualitative criteria (5:22).

Unfortunately, Boucher and MacStravic do not apply this variation to the complete AHP technique. Instead, they use it to calculate values similar to those resulting from the direct method mentioned above (5:21).

Chapter Summary and Conclusions

The federal government calls the process of choosing from several alternatives that are competing for limited funding, economic analysis. The private sector calls this process capital budgeting. Analyses performed using these techniques appear to stress a reliance on the financial aspects of the decision. Even when the non-financial quantitative and qualitative criteria are considered in a decision, a variety of methods are used and no single systematic method is standard.

The AHP is one method which attempts to incorporate non-financial quantitative and qualitative criteria into the decision process by quantifying the judgments of a person or persons who are best qualified to make the appropriate judgments. In most cases, the person who is best qualified to make decisions regarding the alternatives is the decision maker who is nearest the problem. The AHP has an added benefit that no other multiple-criterion decision tools provide, a measure of the decision's rationality. The AHP's consistency ratio provides the decision makers with some feedback that indicates the reasonableness of their judgments. Consistency is an important factor to consider in weighing the merits of multiple alternatives. Without some measure of consistency, decisions may be based on erroneous or contradictory information.

Chapter III discusses the specific methodology used in the trial application of the AHP to an Air Force economic analysis.

III. Methodology

Review/Overview

At this point, the problem statement and the investigative questions from Chapter I will be revisited. The first investigative question has been answered. Much has been written concerning the treatment of financial data in capital budgeting/economic analysis problems. The techniques are inconsistently adhered to in practice, however. The process for dealing with other criteria seems to be much less developed.

The Analytic Hierarchy Process (AHP) has been examined in detail. It is an objective systematic multiple criterion decision making (MCDM) tool that 1) handles qualitative criteria, 2) assigns weights to all of the criteria, and 3) is applicable to capital budgeting/economic analysis situations. What still remains is to develop a standardized economic analysis procedure involving the AHP.

The remainder of this chapter discusses the four phases of the methodology underlying the development of the thesis. The methodology began with data collection, and concluded with an analysis of the results from the application of the AHP to the collected data. It included a brief examination of two computer software tools that could assist the decision maker with the calculations involved in the AHP. One of the computer software tools was selected and used to demonstrate the application of the AHP to a previously completed Air Force economic analysis.

Research Methodology

The research process assumed that the problem described in Chapter I was valid and that Saaty's AHP could provide a reasonable estimate of the weights used to rank a number alternatives. The actual process was divided into four phases. Phase I involved the collection of economic analysis data. Phase II involved the investigation of several appropriate MCDM methods. From this list of MCDM methods, the AHP was chosen to perform an economic analysis on a sample of Air Force data provided by the 2750th Air Base Wing, Cost Analysis and Services Branch, Comptroller Division (2750th ABW/FMC) at Wright-Patterson Air Force Base, Ohio. Phase III involved the application of the AHP to the sample data. Phase IV involved an analysis of the results of the application of the AHP in Phase III.

Phase I. In this phase, the researchers gathered sample economic analysis data from the 2750th ABW/FMC (6). The population of economic analyses for this study consisted of all Air Force economic analyses. From this population a sample economic analysis was selected. The sample was a Military Construction Program economic analysis of several alternatives for providing a taxiway system at Wright-Patterson Air Force Base, Ohio. The Taxiway Economic Analysis was originally completed in June 1990 by Mr. Randy Bradley, a cost analyst from the 2750th ABW/FMC (7). When this analysis was first conducted, the analysts examined the costs and benefits associated with each of the alternatives. They used standard government procedures to analyze the quantitative financial costs of the alternatives. No quantitative non-financial or qualitative costs were included in the analysis. The benefit portion of the analysis did not include an assessment of any quantitative benefits, but it did include subjectively assigned quantitative scores for various qualitative factors (7).

Phase II. During this phase of the research process, appropriate MCDM methods were investigated and the AHP was chosen. Based upon its ability to provide consistency checks on management's preferences, the AHP was believed to be a good method for analyzing the quantitative and qualitative data normally associated with an economic analysis. Automan and Expert Choice were two computer implementations of the AHP investigated during this phase (33:4; 3:56). An examination of the two software packages revealed that Automan was a simpler and less-expensive alternative, however, Expert Choice was a more capable software implementation. Expert Choice was selected to perform the analysis because of its capability to solve more complex problems and its capability to perform sensitivity analysis.

Phase III. In this phase, Expert Choice was used to apply the AHP to the sample Air Force economic analysis. Two distinct analyses were performed on the sample data. The first employed the proportional method exclusively. (See Chapter II, page 23, for a discussion of the proportional method.) For the second analysis, the researchers generated pairwise comparison matrices from the existing numerical scores for the qualitative criteria. The data were analyzed with Expert Choice on a microcomputer. Zero-one integer linear programming (see Chapter II, page 28, for a discussion) was not needed here because the alternatives associated with this economic analysis were mutually exclusive and the recommended alternative was the one with the largest score. The data and analysis are presented in detail in Chapter IV.

Phase IV. During this phase, the results were analyzed to demonstrate the effectiveness of the Expert Choice implementation of the AHP as a selection technique. From these results, the researchers developed a set of conclusions and recommendations for the Air Force to use in implementing a systematic procedure to include non-financial criteria in the economic analysis process. These conclusions and recommendations are presented in Chapter V.

Summary

The methodology of this thesis was a somewhat straightforward demonstration of how to use the AHP to conduct an economic analysis. The researchers began the process by gathering a sample Air Force economic analysis. The researchers then investigated several MCDM methods, and chose the Expert Choice implementation of the AHP. Data from the sample economic analysis were used to perform a new economic analysis with

Expert Choice. This study was completed by offering several conclusions and recommendations regarding Air Force usage of the AHP to conduct economic analyses.

Chapter IV presents an analysis of the results obtained from applying the AHP to the Air Force Taxiway Economic Analysis.

IV. Analysis and Findings

Overview

This portion of the research study analyzed an Air Force Military Construction Program that proposed to provide an alternative aircraft taxiway system at Wright-Patterson Air Force Base (AFB), Ohio. The analysis was performed using the Expert Choice implementation of the Analytic Hierarchy Process (AHP). This chapter concludes with a discussion on how applicable the AHP and Expert Choice were to this Air Force economic analysis.

Taxiway Economic Analysis

The Taxiway Economic Analysis (EA) was a study of several alternatives dealing with the movement of aircraft at Wright-Patterson AFB. This study was originally completed on 4 June, 1990 by Mr. Randy Bradley, a cost analyst from the 2750th Air Base Wing Cost Analysis and Services Branch, Comptroller Division (2750th ABW/FMC) (7). The purpose of the analysis was to recommend the most effective solution that provided the following: a) safe, efficient access between the air freight terminal and the southwest end of the primary runway, b) two hazardous cargo pads used in the loading and unloading of cargo aircraft, c) an arm/disarm pad used in the launch and recovery of tactical fighter aircraft, and d) a personnel shelter (7:1).

According to the Taxiway EA, the need for a new taxiway system was identified in the Airfield Pavement Evaluation Report (APER), which was prepared by the Air Force Engineering and Services Center in August 1985. The APER classified the condition of taxiways 8 and 12 as very poor and structurally inadequate (7:2).

Another requirement mentioned in the original EA was the need for two hazardous cargo pads. The existing taxiway system did not provide dedicated space where hazardous cargo could be loaded and unloaded. The old cargo pads were used for aircraft parking as well as for loading and unloading of hazardous cargo. This was considered to be an unacceptable safety hazard (7:2).

The arm/disarm pads and personnel shelter were additional needs cited in the Taxiway EA. The pads were required to arm and disarm ordnance from fighter aircraft flown by the 906th Tactical Fighter Group (TFG). The shelter was required to protect personnel assigned to the loading and unloading of cargo aircraft, and the arming and disarming of ordnance. The Taxiway EA cited an Air Force Manual 86-2 requirement that the "arm/disarm pads and personnel shelter be located as close to the end of the runway as possible to prevent fighter aircraft from taxiing with armed ordnance" (7:2).

A total of six alternatives were considered, two of which were eliminated from further consideration because they did not meet certain mandatory requirements.

Alternative 1. This choice was to "do nothing," or maintain the status quo. In the original study, this alternative was eliminated from consideration because the existing condition of the taxiways was deemed completely inadequate by the APER.

Alternative 2. This alternative was to repair taxiways 8 and 12. It involved removal of the existing concrete on taxiways 8 and 12 and replacing it with new concrete. Some of the existing concrete would be recycled and used as a subbase. The hazardous cargo pads, which were a part of taxiway 12, would remain a part of that taxiway. The arm/disarm pad and personnel shelter would not be constructed under this alternative. These deficiencies were judged not serious enough to eliminate this alternative from further consideration.

Alternative 3. This alternative was to construct a new taxiway 1 to replace a majority of taxiways 8 and 12, and new hazardous cargo pads. It proposed to recycle a large portion of concrete from taxiways 8 and 12 for use in constructing taxiway 1. In addition, it planned to construct a new arm/disarm pad and a personnel shelter.

Alternative 4. This alternative is similar to Alternative 3 except that it would not recycle the concrete from taxiways 8 and 12. The concrete would be removed and discarded.

Alternative 5. This alternative is similar to Alternative 3 except that taxiways 8 and 12 would simply be abandoned.

Alternative 6. This alternative considered several different shorter routes for the taxiways. It was eliminated from further consideration because the alternative routes reduced the amount of available aircraft parking space. In addition, some of the alternative routes did not allow the aircraft adequate clearance between the taxiway and the buildings (7:3-5).

Analysis of Alternatives

In the original study, Alternatives 1 and 6 were deemed infeasible and eliminated from further consideration. Costs and benefits for Alternatives 2 through 5 were analyzed. Analysis was limited to the financial or monetary costs of each alternative, and the qualitative benefits of each alternative. Non-financial costs and quantitative benefits were not considered because they were difficult to identify (7:5,13). The cost results of the Taxiway EA are presented in Table 15. These results show the present value of the design, investment, and operations and maintenance costs for each of the alternatives over a 20-year life cycle. The "high" and "low" present values define the amount of uncertainty in the analyst's estimates of the costs of each alternative. The high values were generated mainly from Automated Air Force Pricing Guide data, and the low values were generated mainly from Wright-Patterson historical unit cost data (7:16,23). Although the low cost values were considered in weighing the risks of the alternatives, the high cost values were emphasized in the actual analysis.

TABLE 15

PRESENT VALUE OF COSTS

Alternative	(High) Present Value	(Low) Present Value
2. Repair Taxiways 8 & 12	$20,865,240	$11,972,584
3. Construct Taxiway 1, Recycle 8 & 12	$19,965,698	$13,425,301
4. Construct Taxiway 1, Demolish 8 & 12	$19,915,593	$13,935,750
5. Construct Taxiway 1, Abandon 8 & 12	$17,555,107	$12,570,294

The original study considered eight qualitative criteria (7:13). The criteria included the following:

a. Taxiway capability of sustaining aircraft weight;

b. A 100 percent operational use rate for the taxiway during loading and unloading of hazardous cargo and explosives;

c. Efficiency and safety of loading and unloading explosives-laden aircraft;

d. Ability to move net explosives weight (NEW) during contingency operations;

e. Maximization of aircraft parking space;

f. Minimization of taxiway congestion for safety of aircraft and aircrew;

g. Efficiency and safety of arm/disarm procedures for the 906th TFG aircraft;

h. Compliance with Air Force regulations.

The analyst who prepared the Taxiway EA assigned a score on a scale of 1 to 10 to each alternative for each criterion. A score of 1 indicated that the alternative was least effective in satisfying that criterion, while a score of 10 indicated that the alternative was most effective. Weights were assigned to the qualitative benefit criteria for use as multipliers in calculating a total quantitative score for each of the alternatives. The weights were either one or two, with two considered to be more important than one (7:15,48-51). These scores and weights were generated with the help of the actual users who submitted the project to be analyzed. The individual scores, individual weights, and total weighted scores for each of the alternatives are displayed in Table 16.

TABLE 16

QUALITATIVE CRITERIA SCORES AND WEIGHTS

Criterion	Weight	Alt 2	Alt 3	Alt 4	Alt 5
Sustain Aircraft Weight	2	10	10	10	5
100% Use of Taxiway (T/W)	2	5	10	10	10
Load/Unload Explosives & Hazardous Cargo	1	2	10	10	10
Ability to Move NEW	1	1	3	3	3
Maximize Aircraft Parking Spaces	1	10	8	8	8
Minimize T/W Congestion	2	3	10	10	10
Arm/Disarm for 906th TFG	1	2	10	10	10
AF Regulation Compliance	2	2	10	10	5
TOTAL WEIGHTED SCORE		55	111	111	91

In addition to the eight qualitative criteria that were assigned scores, environmental concerns was a criterion considered in the conclusions and recommendations section of the Taxiway EA. The environmental concerns criterion was not assigned a numerical score, but it was used as a basis for forming recommendations (7:24,25). As a result, Alternative 3 was the highest rated alternative based on the qualitative criteria.

In the original study, Alternative 3 was the recommended choice (7:25). The original study implicitly assigned a significant level of importance to the qualitative criteria relative to the cost criterion. Considering only costs, Alternative 5 would be the preferred choice; however, this alternative was rejected because of its much less than optimal rating on the qualitative criteria. Alternative 2 was ruled out because it received the lowest rating on both the cost and the benefits criteria. The difference in the costs for Alternatives 3 and 4 were insignificant and the total weighted criterion scores for these alternatives were equal. Therefore, the environmental criterion was the deciding factor in the choice of Alternative 3 over Alternative 4.

Analysis Using Expert Choice

Expert Choice was used to perform two separate AHP analyses and a sensitivity analysis of the data provided in the Taxiway EA. The first AHP analysis was accomplished with the proportional method. (See Chapter II, page 23, for a discussion of the proportional method.) This was made possible by the availability of quantitative data that could be used to describe the qualitative portions of the original problem. Based on the results of the first AHP analysis, a sensitivity analysis was conducted. In the sensitivity analysis, the effect that the uncertainties of the costs of the alternatives had on the overall ratings was examined. Then the weight of the cost criterion was varied to examine its effect.

The second AHP analysis was done in a manner that was identical to the first, except that pairwise comparisons were used to rate each alternative with respect to the qualitative criteria. (See Chapter II, page 19, for a discussion of the pairwise comparison process.) These pairwise comparisons, which were performed by the researchers, were based on the numerical scores for the alternatives with respect to the qualitative criteria. No sensitivity analysis was performed on the results of the second AHP analysis.

Both AHP analyses considered the environmental impact as an additional qualitative criterion. Based on an overall familiarity with the taxiway situation gained through a thorough examination of the original study, the environmental criterion was assigned a weight of one by the researchers. The numerical scores for the various alternatives with respect to the environmental criterion were assigned by the researchers as shown in Table 17.

The cost criterion was not assigned a weight in the original study. For the AHP analyses, the cost criterion was assigned a weight of four by the researchers because cost is usually given a high priority by the Air Force. As in the original study, the high estimates of present value costs were used in the basic AHP analyses.

TABLE 17

ENVIRONMENTAL CRITERION SCORES

Alternative	Score
2	7
3	10
4	1
5	4

First Analysis. This AHP analysis was started by specifying a hierarchical model for the quantitative data contained in Tables 15 through 17. A representation of the top three levels of the model, constructed with Expert Choice, is shown in Figure 6. The lower levels of the model are shown in Figures 7 through 9. This version of Expert Choice limited the total number of branches for any single node of the hierarchy to seven. Therefore, the nine qualitative benefits were divided into two separate groups. The grouping of the benefit criteria had no material effect on the outcome of the analysis. If pairwise comparisons had been used to determine the relative weights of these criteria, more attention to this grouping would have been in order. The following is a list of abbreviations used in Figures 6 through 9 (limited to eight characters by Expert Choice) and their corresponding definitions:

GOAL --- Select an Effective Method of Updating the WPAFB Taxiway System.
100% USE --- 100 Percent Operational Use of Taxiway During Loading of Cargo.
AFR COMP --- Compliance with Air Force Regulations.
ARM/DISA --- Efficiency and Safety of Arm/Disarm Procedures.
BEN'S #1 --- The First Group of Benefits for the Alternatives.
BEN'S #2 --- The Second Group of Benefits for the Alternatives.
COST --- Cost of the Alternatives.
EFF&SAFE --- Efficiency and Safety of Loading/Unloading Explosives-Laden Aircraft (A/C).

ENVIRONM	---	Environmental Concerns About the Disposal of Concrete.
MOVE NEW	---	Ability to Move Net Explosives Weight (NEW) During Operations.
PR VALUE	---	Present Value of the Project's Cost.
PRK SPAC	---	Maximization of Aircraft Parking Space.
T/W CON	---	Minimization of Congestion for Safety of Aircrew & A/C.
WEIGHT	---	Sustain Aircraft Weight.
ALT 2	---	Alternative 2. Repair Taxiways 8 & 12.
ALT 3	---	Alternative 3. Construct Taxiway 1, Pads, Shelter, and Recycle.
ALT 4	---	Alternative 4. Construct Taxiway 1, Pads, Shelter, and Demolish.
ALT 5	---	Alternative 5. Construct Taxiway 1, Pads, Shelter, and Abandon.
L	---	LOCAL SIGNIFICANCE
G	---	GLOBAL SIGNIFICANCE

"Local significance" means with respect to the connecting block from the next higher level, or parent block. The sum of all of the local significance values for any given *node* in the hierarchy will always be one. "Global significance" means with respect to the overall system. The sum of all of the global significance values for any given *level* of the hierarchy will always be one. A local value is converted into a global value by multiplying the local value by the global value of its parent block. The local and global values in Figures 6 through 9 were derived through the proportional method from the data in Tables 15 through 17. As an example, notice the local values for the alternatives with respect to the "Move NEW" criterion in Figure 8. The total value for all four alternatives according to Table 16 is ten. Each alternative's local value is merely its raw score divided by ten.

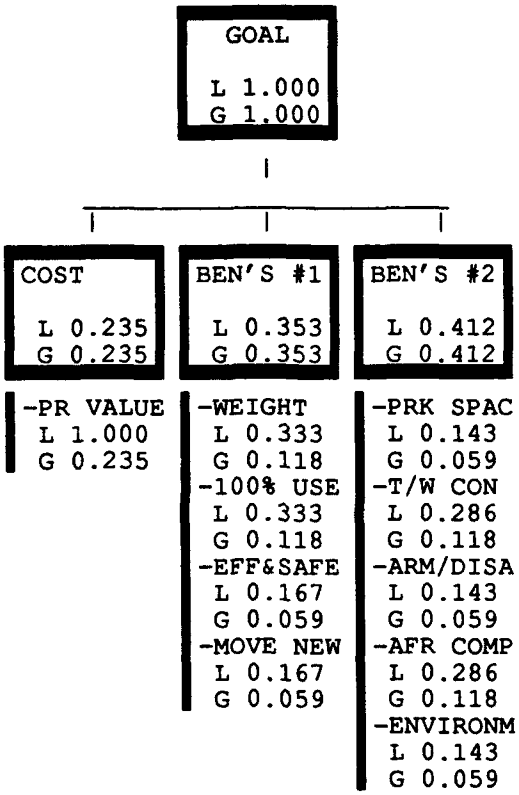

Figure 6. Top Three Levels of Expert Choice Model

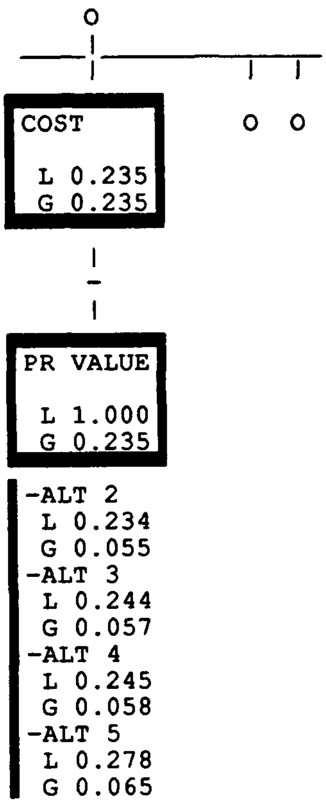

Figure 7. Lower Levels for Cost Criterion

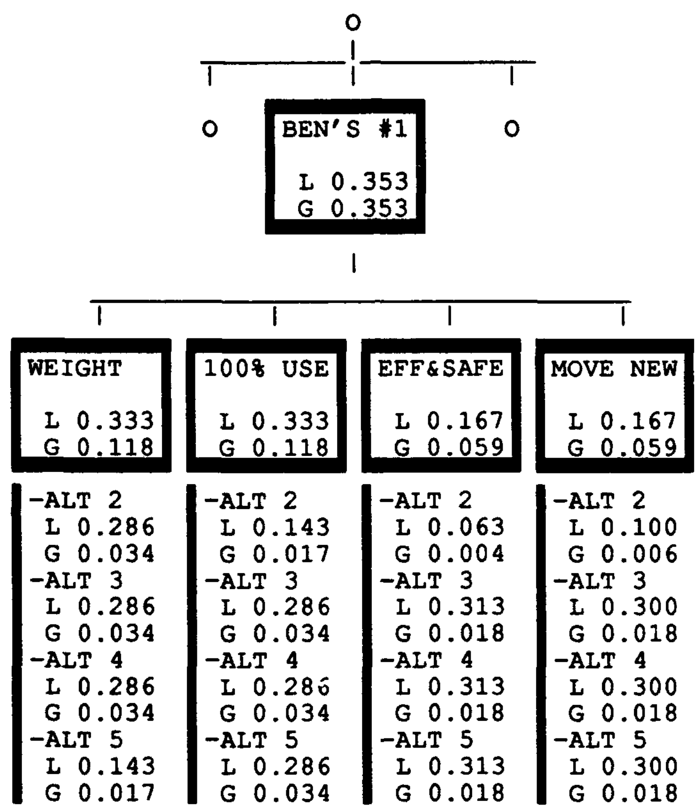

Figure 8. Lower Levels for First Group of Benefits

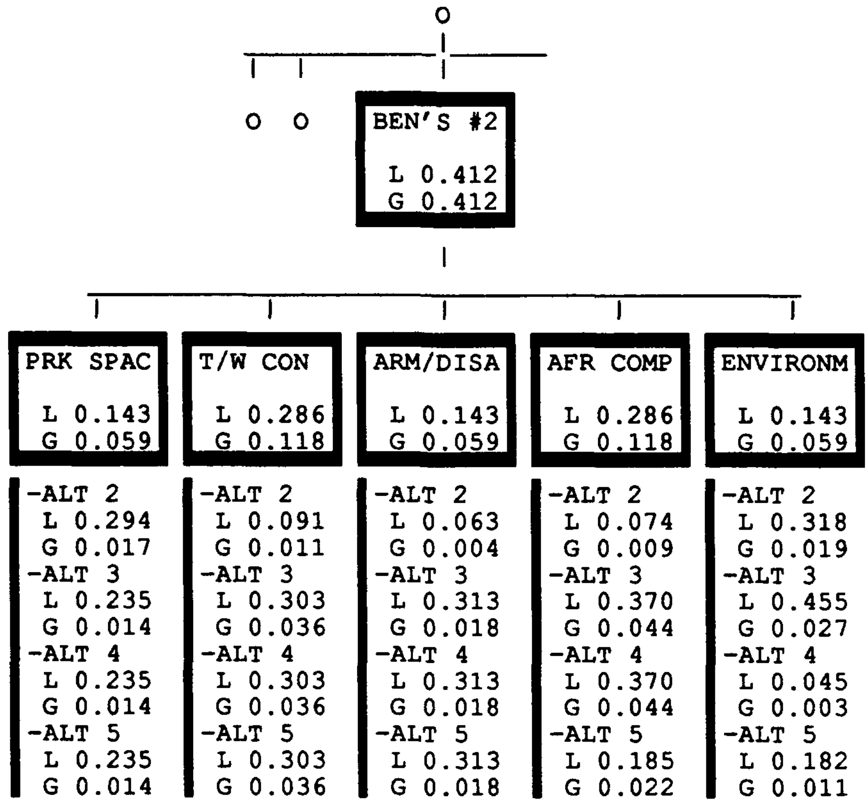

Figure 9. Lower Levels for Second Group of Benefits

Table 18 is a collection of the global values from Figures 6 through 9.

TABLE 18

HIERARCHY GLOBAL VALUES

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
COST =0.235				
.	PR VALUE =0.235			
.	.	ALT 2 =0.055		
.	.	ALT 3 =0.057		
.	.	ALT 4 =0.058		
.	.	ALT 5 =0.065		
BEN'S #1 =0.353				
.	WEIGHT =0.118			
.	.	ALT 2 =0.034		
.	.	ALT 3 =0.034		
.	.	ALT 4 =0.034		
.	.	ALT 5 =0.017		
.	100% USE =0.118			
.	.	ALT 2 =0.017		
.	.	ALT 3 =0.034		
.	.	ALT 4 =0.034		

```
.                  .                   ALT 5     =0.034
.                  EFF&SAFE =0.059
.                  .                   ALT 2     =0.004
.                  .                   ALT 3     =0.018
.                  .                   ALT 4     =0.018
.                  .                   ALT 5     =0.018
.                  MOVE NEW =0.059
.                  .                   ALT 2     =0.006
.                  .                   ALT 3     =0.018
.                  .                   ALT 4     =0.018
.                  .                   ALT 5     =0.018
BEN'S #2 =0.412
.                  PRK SPAC =0.059
.                  .                   ALT 2     =0.017
.                  .                   ALT 3     =0.014
.                  .                   ALT 4     =0.014
.                  .                   ALT 5     =0.014
.                  T/W CON  =0.118
.                  .                   ALT 2     =0.011
.                  .                   ALT 3     =0.036
.                  .                   ALT 4     =0.036
.                  .                   ALT 5     =0.036
.                  ARM/DISA =0.059
.                  .                   ALT 2     =0.004
.                  .                   ALT 3     =0.018
.                  .                   ALT 4     =0.018
.                  .                   ALT 5     =0.018
.                  AFR COMP =0.118
.                  .                   ALT 2     =0.009
.                  .                   ALT 3     =0.044
.                  .                   ALT 4     =0.044
.                  .                   ALT 5     =0.022
.                  ENVIRONM =0.059
.                  .                   ALT 2     =0.019
.                  .                   ALT 3     =0.027
.                  .                   ALT 4     =0.003
.                  .                   ALT 5     =0.011
```

The results of applying the final step of the AHP to the values in Table 18 are presented in Table 19. Expert Choice calculates an overall inconsistency index, which is computed from inconsistency ratios. These inconsistency ratios are equivalent to the consistency ratio described in Chapter 2. The overall inconsistency index of zero shown in Table 19 indicates that the judgments were perfectly consistent. This result is a direct fallout of the fact that the ratings were based on numerical values, which allowed the use of the proportional method. Inconsistency ratios are not used in the proportional method. As in the original study, Alternative 3, with a rating of 0.299, was indicated as the preferred choice.

TABLE 19

RATINGS OF THE ALTERNATIVES

OVERALL INCONSISTENCY INDEX = 0.00

Alternative	Rating
ALT 2	0.174
ALT 3	0.299
ALT 4	0.275
ALT 5	0.252
	=====
TOTAL	1.000

Sensitivity Analysis. This section examined the sensitivity of the overall ratings for the alternatives to the cost uncertainties expressed in the original study, and then to the weight of the cost criterion. First, the low-cost present values of each alternative were substituted for the high-cost present values. Figure 10 shows the revised cost branch and the resulting scores for the low-cost present values, which were generated by Expert Choice. The scores for the cost and present value criteria did not change as a result of adjusting the present values of the alternatives; however, the scores for the alternatives did change.

The effect of the adjusted cost values on the overall ratings of the alternatives is shown in Table 20. The overall impact on the ratings for the alternatives was slight. The ratings for Alternatives 3, 4, and 5 decreased by a small amount from the previous ratings, while Alternative 2 increased by a somewhat larger amount. The small changes in the ratings occurred because the cost criterion was not heavily weighted. The increased rating for Alternative 2 was due to its greater relative decrease in the present value of cost. The ranking of the alternatives was unchanged.

```
           O
      _____|______________
           |        |  |
  ┌─────────────┐
  │COST         │   O  O
  │             │
  │ L 0.235     │
  │ G 0.235     │
  └─────────────┘
           |
           -
           |
  ┌─────────────┐
  │PR VALUE     │
  │             │
  │ L 1.000     │
  │ G 0.235     │
  └─────────────┘
  |-ALT 2
  |  L 0.270
  |  G 0.064
  |-ALT 3
  |  L 0.241
  |  G 0.057
  |-ALT 4
  |  L 0.232
  |  G 0.055
  |-ALT 5
  |  L 0.257
  |  G 0.061
```

Figure 10. Revised Cost Branch

TABLE 20

REVISED RATINGS OF THE ALTERNATIVES

OVERALL INCONSISTENCY INDEX = 0.00

Alternative	Rating
ALT 2	0.183
ALT 3	0.298
ALT 4	0.272
ALT 5	0.247
	=====
	1.000

Figure 11 presents the Expert Choice sensitivity analysis of the weight of the cost criterion, as the relationships among the benefits criteria are held constant. The effect of varying the weight of the cost criterion, shown on the horizontal axis, is recorded as ratings for the alternatives on the vertical axis. The vertical dotted line indicates the AHP value that reflects the original weight given to the cost criterion. The intersections of this dotted line with the lines designating the alternatives denote the vertical axis ratings given in Table 20. As the weight of the cost criterion increases, Alternative 2, with its smaller present value, receives a progressively higher overall rating. Alternative 2 becomes the most attractive option when the rating of the cost criterion is increased to a value of 0.88 or higher.

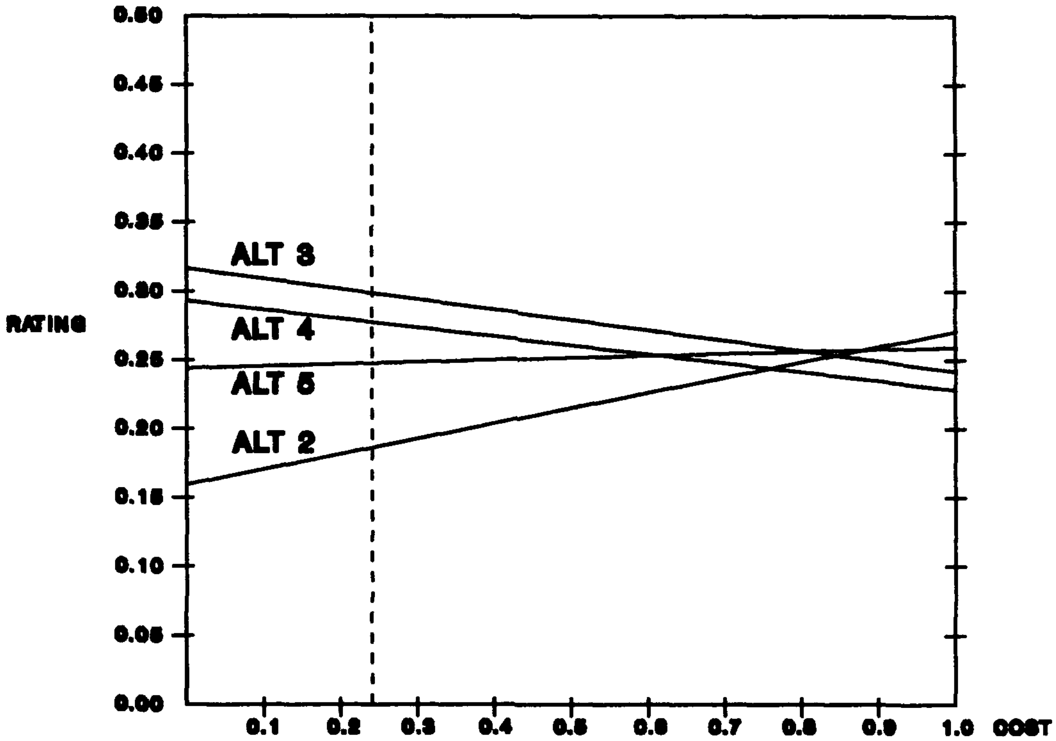

Figure 11. Cost Sensitivity For Nodes Below: Goal

Second Analysis. This AHP analysis used the same overall model and criterion weights as the first AHP analysis. The high-cost present values were used as they were in the first analysis, with the proportional method applied to calculate the ratings for the cost branch. Pairwise comparisons were performed by the researchers on the alternatives with respect to each of the benefit criteria. To demonstrate the pairwise comparison technique, the data shown in Tables 21 through 29 were based on the researchers' subjective assessments of what management's preferences might have been.

The values of the judgments in Tables 21 through 29 range from 1.0 to 9.9, with 1.0 indicating that the two alternatives are equal with respect to the given criterion. A value of 9.9 indicates that the alternative in the row is about ten times as preferred as the alternative in the column. The judgement values in parentheses indicate the relative preference for the alternative in the column to the one in the row. For example, the value of (2.0) in the Alternative 2 row and the Alternative 3 column of Table 21 suggests that Alternative 3 is twice as preferred as Alternative 2.

Unlike the proportional method, inconsistencies sometimes arise with the pairwise comparison or *eigenvalue* method. Some of the judgments entered in Tables 21 through 29 were intended by the researchers to be inconsistent. Table 21 is an example of judgments that led to an inconsistency ratio of greater than 0.1.

TABLE 21

JUDGMENTS WITH RESPECT TO WEIGHT

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(2.0)	(2.0)	6.0
ALT 3			1.0	2.0
ALT 4				2.0
ALT 5				

INCONSISTENCY RATIO = 0.158

TABLE 22

JUDGMENTS WITH RESPECT TO 100% USE

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(2.0)	(2.0)	(2.0)
ALT 3			1.0	1.0
ALT 4				1.0
ALT 5				

INCONSISTENCY RATIO = 0.000

TABLE 23

JUDGMENTS WITH RESPECT TO EFFECTIVE AND SAFE LOADING

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(5.0)	(5.0)	(5.0)
ALT 3			1.0	1.0
ALT 4				1.0
ALT 5				

INCONSISTENCY RATIO = 0.000

TABLE 24

JUDGMENTS WITH RESPECT TO THE MOVEMENT OF NEW

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(3.0)	(3.0)	(3.0)
ALT 3			1.0	1.0
ALT 4				1.0
ALT 5				

INCONSISTENCY RATIO = 0.000

TABLE 25

JUDGMENTS WITH RESPECT TO PARKING SPACE

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		1.3	1.3	1.3
ALT 3			1.0	1.0
ALT 4				1.0
ALT 5				

INCONSISTENCY RATIO = 0.000

TABLE 26

JUDGMENTS WITH RESPECT TO TAXIWAY CONGESTION

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(3.3)	(3.3)	(3.3)
ALT 3			1.0	1.0
ALT 4				1.0
ALT 5				

INCONSISTENCY RATIO = 0.000

TABLE 27

JUDGMENTS WITH RESPECT TO ARM/DISARM PAD

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(5.0)	(5.0)	(5.0)
ALT 3			1.0	1.0
ALT 4				1.0
ALT 5				

INCONSISTENCY RATIO = 0.000

TABLE 28

JUDGMENTS WITH RESPECT TO AF REGULATION COMPLIANCE

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		(8.0)	(8.0)	(2.0)
ALT 3			1.0	2.0
ALT 4				2.0
ALT 5				

INCONSISTENCY RATIO = 0.022

TABLE 29

JUDGMENTS WITH RESPECT TO THE ENVIRONMENT

	ALT 2	ALT 3	ALT 4	ALT 5
ALT 2		1.0	7.0	1.8
ALT 3			9.9	1.7
ALT 4				(3.0)
ALT 5				

INCONSISTENCY RATIO = 0.015

Figures 12 and 13 show the benefit branches resulting from the Expert Choice processing of the pairwise comparison and weight data. The scores of the benefit criteria with respect to the overall goal did not change from the previous AHP analysis. The scores for the alternatives with respect to the individual criteria changed slightly.

Table 30 presents the overall results of the application of Expert Choice to the cost, weight, and pairwise comparison data. The ratings for the alternatives with respect to the overall goal varied by a small amount, but the rankings of these alternatives did not change.

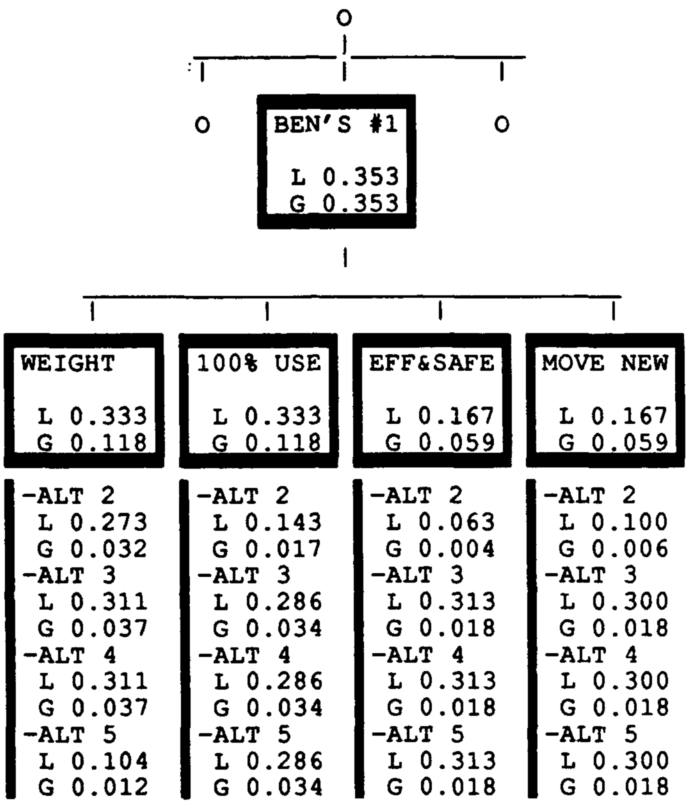

Figure 12. First Benefits Branch

Chapter Conclusion

The AHP and the Expert Choice software were judged by the researchers to be effective in conducting the additional analyses of the Taxiway EA. The AHP provided a systematic method for considering qualitative criteria, and for combining quantitative and qualitative criteria. Expert Choice removed some of the burden of having to calculate the weights and the ratings manually. It also served as a tool for conducting the pairwise comparisons in a logical manner.

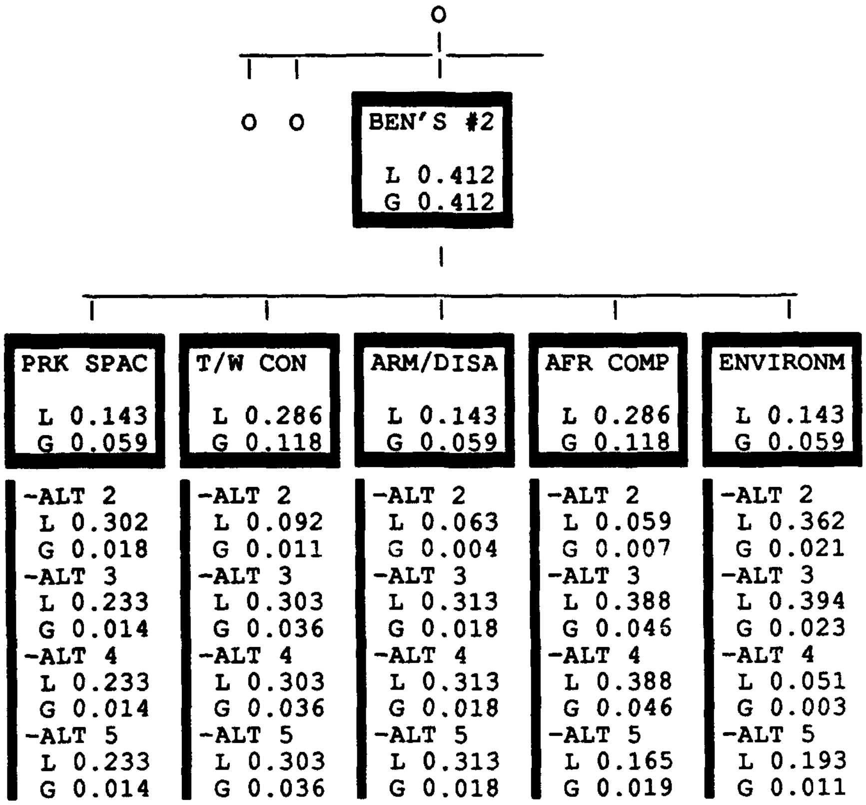

Figure 13. Second Benefits Branch

TABLE 30

RATINGS OF THE ALTERNATIVES RESULTING FROM PAIRWISE DATA

OVERALL INCONSISTENCY INDEX = 0.01

Alternative	Rating
ALT 2	0.174
ALT 3	0.300
ALT 4	0.280
ALT 5	0.246
	=====
	1.000

The version of Expert Choice used in this study, a student version, limited the number of branches for each node to seven. This made it necessary to split the benefit criteria into two separate groups. This was not a significant detriment in and of itself; however, it precluded a more thorough sensitivity analysis. The built-in sensitivity analysis capability of Expert Choice was only useful in determining the sensitivity of the overall ratings for the alternatives to changes in the criteria directly below the overall goal. This limitation to the built-in capability prevented the consideration of variations in the individual benefit criteria. Although the two benefit groups were available for sensitivity analysis, the values of the alternatives were plotted with respect to the individual benefit group only. These values were not meaningful to the question of determining the sensitivity of the overall ratings of the alternatives to changes in the weights of the individual benefit criteria. Finally, Expert Choice did not allow an automated sensitivity analysis to be performed at any level below the benefit groups. This precluded any kind of automated sensitivity analysis of variations in the scores of the alternatives with respect to individual criteria.

In analyzing the Taxiway EA, the prior availability of weights for the benefit criteria, and numerical scores for the alternatives with respect to these criteria allowed the exclusive use of the AHP's proportional method. Consequently, pairwise comparisons were not performed in the first AHP analysis. The prior availability of numerical weights for criteria, and scores for alternatives is not expected to be the typical case. In an original economic analysis, this information will not have been generated previously. Without this information, pairwise comparisons would be performed at this stage of the analysis.

As demonstrated by the second AHP analysis of the taxiway data, the capability to perform pairwise comparisons is a valuable function of the AHP and Expert Choice in a case where quantitative data for the criteria and alternatives is not available. The pairwise comparison process is systematic and surprisingly fast. Pairwise comparisons simplify the analysis process by decreasing the number of criteria or alternatives that decision makers must weigh at one time. The consistency check helps decision makers to refine their judgment process.

<u>Summary</u>

This chapter presented a brief description of a previously conducted economic analysis of a proposed taxiway system at Wright-Patterson AFB, Ohio. The data from the taxiway study was then used to perform two new analyses with a computer implementation of the AHP called Expert Choice. The first AHP analysis employed Expert Choice and a set of purely quantitative data to rate and rank the taxiway alternatives. The second AHP analysis used Expert Choice, pairwise comparison data, and a portion of the quantitative data to rate and rank the alternatives. The conclusion to this chapter suggested that Expert Choice and the AHP were helpful tools for the performance of an economic analysis.

The next chapter of this thesis presents several conclusions derived from this study and offers several recommendations regarding the possible employment of a computerized version of the AHP by the Air Force.

V. Conclusions and Recommendations

Summary of Chapters I through IV

Chapter I of this study introduced the issue and established the significance of the problem. The central issue was the lack of a definitive method for conducting a thorough and systematic Air Force economic analysis (EA) involving qualitative criteria. It was discovered that many Air Force EAs are conducted with a variety of heuristic techniques that were developed out of necessity.

The second chapter of this research paper investigated the background of capital budgeting and several multiple criterion decision making (MCDM) methods. The process of committing funds to long-term investment decisions is called capital budgeting in the private sector and economic analysis in the military. Economic analyses are inherently subjective and therefore vulnerable to the biases of those conducting the analysis. This problem is especially acute when the analysis involves qualitative considerations. There are several MCDM methods that offer ways to manage this problem. The Analytic Hierarchy Process (AHP) is one viable MCDM technique. It is a systematic method for incorporating qualitative factors into the decision process, and for checking the consistency of the decision maker's judgments. Expert Choice is a computerized implementation of the AHP.

Some capital budgeting decisions involve the selection of a single alternative solution, while others involve the selection of more than one alternative. The combination of the AHP and zero-one integer linear programming was discovered to be an appropriate method for determining the best multiple-alternative solution.

Chapter III outlined the methodology of this research effort. The objective of the methodology was to demonstrate that the Expert Choice implementation of the AHP could be used to perform an Air Force EA in a logical manner. The methodology was divided into four distinct phases.

The first phase involved the collection of Air Force data. The second phase was the investigation of various MCDM methods. The third phase was the application of the AHP to the data. The final phase was the analysis of the results of the application of the AHP.

The fourth chapter described the application of Expert Choice to data extracted from a previously conducted Air Force EA of the taxiway system at Wright-Patterson AFB, Ohio. This chapter began with a brief description of the original EA, which was completed in June 1990. Data from the original study was analyzed with Expert Choice by applying two separate approaches. One of the approaches included sensitivity analyses of the alternatives to changes in the cost values and to variations in the relative weight of the cost criterion. Based on the results of these analyses, it was concluded that the AHP and Expert Choice were helpful tools for conducting an EA.

Conclusions

The AHP is a technique for accomplishing a thorough and systematic EA, especially one involving qualitative factors. Although there are other MCDM methods available for dealing with quantitative and qualitative criteria, these methods, in general, do not effectively incorporate qualitative considerations. The AHP normalizes the units of the various criteria, thus allowing the direct comparison of two or more factors measured on dissimilar scales. It accomplishes this by dividing the overall problem into manageable parts, which can be compared two at a time using a technique called pairwise comparison. Pairwise comparisons simplify the judgments required of a decision maker by limiting the number of criteria or alternatives weighed in a single comparison to two.

One of the primary strengths of the AHP is that it provides consistency checks on the decision maker's judgments. These consistency checks are an indication of how logical the comparisons of the criteria and the alternatives were. Without such checks, potentially contradictory, and therefore meaningless, judgments may be incorporated into the analysis resulting in an invalid outcome.

Expert Choice is one computer software version of the AHP. It provides an automated capability to analyze multiple criteria and alternatives, and to select the best solution to a problem. In addition, it provides the capability to analyze and graph the sensitivity of the alternative solutions to variations in the weights of the criteria. Although Expert Choice does not permit graphical sensitivity analysis of changes in the scores of the alternatives with respect to the criteria, it is possible to input various combinations of alternative scores manually. Expert Choice can then be run to generate an individual outcome for each combination of scores.

In some situations, the alternatives are not mutually exclusive, and more than one alternative can be chosen simultaneously. In this case, the AHP and zero-one integer linear programming can be combined to select an optimal combination of alternatives. The ratings provided by the AHP would be used as part of the input to zero-one integer linear programming.

Recommendations to the Air Force

This study has demonstrated that it is practical for the Air Force to employ the AHP to perform EAs involving multiple quantitative and qualitative factors. Expert Choice is an effective and efficient software tool for an analysis of this type. Expert Choice is an easy to use, menu-driven program that requires little or no training. Once an analyst became familiar with its use, no additional training in the AHP would be necessary. There are other software packages available, such as Automan, which are less expensive, but less capable. Expert Choice, or an equivalent software package, should be made available as an aid in selecting the best alternative in all future applicable Air Force EAs.

All cost analysis organizations throughout the Air Force should acquire a software version of the AHP. The field-level cost analysis organization should continue to prepare the complete EA package. The cost analyst should process all financial data in accordance with current directives and regulations. After completing the financial analysis and collecting all of the pertinent non-financial data, a decision hierarchy suitable for use with the selected software implementation of the AHP should be formed. A representative from the requesting organization should perform the pairwise comparisons necessary to assign weights to the criteria and values to the alternatives. After satisfactorily resolving any unacceptable inconsistencies resulting from the pairwise comparison process, the basic analysis could be completed by the cost analyst. Once this is done, appropriate sensitivity analyses should be conducted to investigate the likelihood that uncertainties in the data would influence the outcome. The complete analysis process should be documented so that it could be replicated. Only the final results from the process, however, along with a statement that they were obtained through the use of the AHP, would need to be included in the executive summary portion of the package.

The Air Force should continue to coordinate EA packages in accordance with current procedures. There will always be some measure of subjectivity in the EA process. The results of the analysis should therefore continue to be used only as one input into the final selection process. The ultimate decision should be based on the needs of the Air Force.

Suggestions for Further Study

An area for further study is the application of the AHP to problems with non-mutually exclusive alternatives. This additional research could examine the effectiveness of applying zero-one integer linear programming to the ratings of the alternatives provided by the AHP. Data from EAs with non-mutually exclusive alternatives would need to be gathered and then analyzed with the AHP and zero-one integer linear programming.

Another idea for further study would be to find an active EA project. An original analysis could then be conducted with the AHP.

Appendix: Branch and Bound Example

The Air Force may be considering three alternative military construction projects. The first alternative may be to construct a new gym, the second may be to construct a new road, and the third may be to construct a new auditorium. A hypothetical set of results from using the AHP is presented in Table 31. This table also shows the costs for each of the alternatives and a budget constraint for the solution.

TABLE 31
PROJECT ALTERNATIVES

Project	AHP Rating	Rank	Cost	Total Budget
Gym (x_1)	.4	1	$100,000	
Road (x_2)	.35	2	$50,000	
Auditorium (x_3)	.25	3	$50,000	$100,000

From Table 31, the zero-one programming problem can be formulated as follows:

Maximize $$f = .4x_1 + .35x_2 + .25x_3 \quad (12)$$

subject to $$100000x_1 + 50000x_2 + 50000x_3 \leq 100000$$

$$x_1, x_2, x_3 = 0 \text{ or } 1$$

The branch and bound solution tree for the zero-one programming problem is shown in Figure 14. The steps that were used to solve this problem are

Step 1. All the x_j's were set to zero giving an f_L value of zero. The variables were all considered free.

Step 2. In this step, x_1 was selected and assigned values of zero and one, thus creating two branches from the top node.

Step 3. At node 2, f_U was calculated by the equation

$$f_U = .4x1 + \sum_{\substack{\text{free} \\ \text{variables}}} c_j = 0.0 + 0.35 + 0.25 = 0.6 \quad (13)$$

At node 3, f_U was also calculated in a similar manner with a result of 1.0.

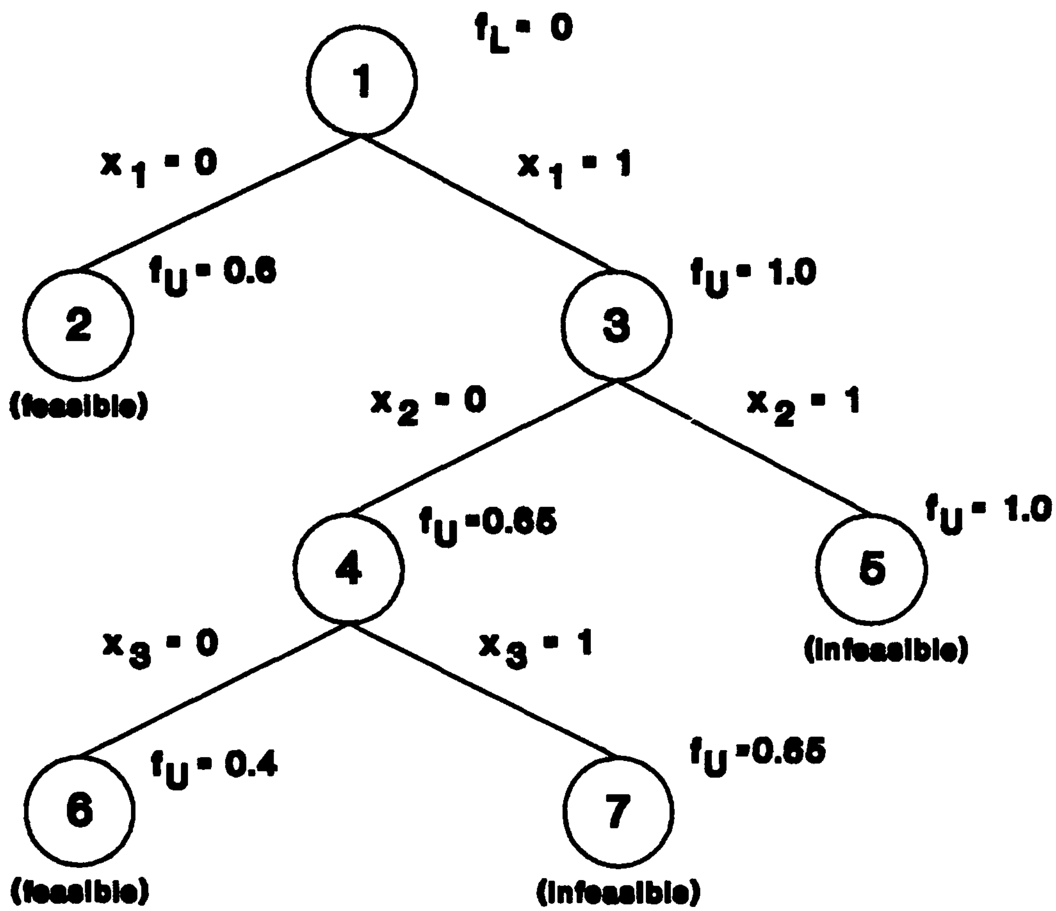

Figure 14. Branch and Bound Example

<u>Step 4</u>. The most recently created partial solution occurred at node 3, where $f_U = 1.0 > f_L$. The upper bound did not generate a feasible completion, therefore, the value of f_L remained at zero. There were remaining feasible solutions.

<u>Step 5</u>. Solutions remained, therefore, Step 2 became the next step.

Step 2. At this step, x_2 was selected and assigned a value of zero and one creating two more branches.

Step 3. At nodes 4 and 5 the values for f_U were calculated as before resulting in values of 0.65 and 1.0, respectively.

Step 4. The solution at node 5 is an infeasible one, therefore, it can be eliminated from further consideration. At node 4 the upper bound did not generate a feasible solution.

Step 5. There are feasible solutions remaining, so go to Step 2.

Step 2. x_3 was assigned values of zero and one.

Step 3. Values of f_U were 0.4 for node 6 and 0.65 for node 7.

Step 4. The solution at node 7 was infeasible. Node 6 resulted in a feasible solution with $f_U = 0.4 > 0.0$, consequently, 0.4 became the new value of f_L, and the solution $x_1 = 1$, $x_2 = 0$ and $x_3 = 0$ became the current solution. Because one of the partial solutions was eliminated, Step 4 was repeated in the next paragraph.

Step 4. The most recently created partial solution occurred at node 2. The value of $f_U = 0.6 > f_L = 0.4$, therefore, 0.6 became the value of f_L, and $x_1 = 0$, $x_2 = 1$ and $x_3 = 1$ became the current solution.

Step 5. There were no remaining partial solutions, consequently, the optimal solution for this example was $x_1 = 0$, $x_2 = 1$, and $x_3 = 1$. This solution suggested that the decision makers should choose the second and third alternatives, build a new road and build an auditorium. The resulting overall rating for this combined solution was 0.6.

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Captain Jeffrey L. Battin was born on December 15, 1961 in Des Moines, Iowa. He graduated from Fort Dodge Senior High in Fort Dodge, Iowa in 1980. In 1985, he graduated from Iowa State University in Ames, Iowa with a Bachelor of Science degree in Computer Science. In 1986, he attended Air Force Officer's Training School where he received his commission. Upon commissioning, he attended communications technical training at Keesler Air Force Base (AFB), Mississippi. His first assignment was to the 28th Air Division at Tinker AFB, Oklahoma. While at the 28th Air Division, he was a requirements officer fcr C-130 aircraft, and eventually became the chief of requirements for those same aircraft. His next assignment was to the Air Force Institute of Technology in May 1991.

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13. ABSTRACT *(Maximum 200 words)*
This study examined the applicability of a multiple criterion decision making (MCDM) method, known as the Analytic Hierarchy Process (AHP), to economic analysis decisions involving project selection. Through a survey of the literature and current practices, it was determined that qualitative criteria were not adequately represented in a typical economic analysis of projects. Several MCDM methods were examined and the AHP was found to be the most promising technique to rate projects on a ratio scale. Two types of project selection problems, those involving non-mutually exclusive alternatives and those involving mutually exclusive alternatives, were examined. It was determined that the AHP was applicable to both types of problems. An investigation of the literature regarding non-mutually exclusive problems revealed that zero-one programming could be used to select a subset of the alternatives with the largest total AHP rating. With the help of a software package called Expert Choice, the AHP was then applied to a previously completed Air Force econmic analysis (with mutually exclusive alternatives) and the results were evaluated. This study concluded with the recommendation that the Air Force formally adopt the AHP into its economic analysis procedures.

14. SUBJECT TERMS
Analytic Hierarchy Process, Linear Programming, Decision Making, Economic Analysis, Linear Algebra, Budgets

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